Management of the Parameters of the Explosive Impact on the Soil Mass Due to the Use of Low-Density Explosives

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Abstract

On the basis of numerical calculations of the problem of the explosion of cylindrical charges of explosive substances in soils, the dependences of maximum pressure, maximum and residual deformations for various types of explosive substances on time and distance are obtained. It is established that the lowest peak pressure with the longest duration of the explosive pulse is observed for charges based on foamed types of explosives, both conventional and treated with ultrasonic radiation. The maximum pressure of these types of explosives is 20–49% less, and the duration of the explosive impulse is in 3–3.5 times longer than compared to the standard low-density explosive – igdanite. The low value of the peak detonation pressure, achieved by reducing the density of explosives, reduces the volume concentration of the energy of the charges, which, in turn, increases the efficiency of the explosive transformation energy in the far zone. The growth time of the explosive impulse of charges based on foamed explosives, both conventional and treated with ultrasonic radiation, is in 2.47 times greater than for igdanite. It is found that in the near zone during the explosion of an igdanite charge, significantly higher values of hydrostatic pressure and maximum volumetric deformation are achieved than in the case of a foamed explosive explosion, which is a consequence of higher detonation characteristics of igdanite: density, pressure at the Jouget point, detonation rate. The time to reach the maximum pressure and deformation during an igdanite explosion is much shorter, because the detonation rate of igdanite is higher than that of foamed explosives. The parameters of shock waves during explosions of charges of new mixed explosives in the middle zone can be compared with the same parameters from traditional industrial explosives, such as igdanite, and in the far zone of the explosion, they exceed them. The difference in the maximum volumetric deformations in igdanite explosions is 7–15% compared to the explosions of foamed explosive and foamed explosive treated with ultrasound, respectively. When detonating a sonicated foamed explosive, the residual deformation is 9–10% greater than when detonating a non-sonicated foamed explosive charge.

Keywords: *mixed explosives, subsidence soils, mathematical simulation*

1. Introduction

The main methods of management of the parameters of the explosive impulse are to control the contact impact of explosive charges on the surrounding array, the order of detonation of the charges. The nature of such influence is defined by: a) properties of explosives materials, chemical composition, concentration; b) density, dispersion and geometric parameters of the charge; c) nature of initiation; d) other structural features of the charge; e) mechanical properties of the array in the contact zone; e) the order of detonation.

The variety of practical applications of explosives, explosive structures and properties of massifs disturbed by an explosion objectively create prerequisites for the most rational use of explosion energy for various purposes in construction and mining in general under certain conditions.

One of the unsolved problems is the stabilization of detonation in non-cartridge charges of considerable length. There is a number of reasons for non-stationary explosive disturbance and attenuation of the detonation process, among which the most significant are: a) non-uniformity of the components of explosive substances and the properties of heterogeneous (multiphase) mediums; b) discharge action of the charge boundary; c) non-water resistance (soaking), due to the hydrophobicity of the main component, saltpeter; e) changing the parameters of the explosive transformation at the contact of different explosive substances.

There are other problems associated with the action of the explosion in the external environment. If a full explosive decomposition of the charge occurs, then the necessary amplitude of the explosive pulse, emitted into the medium, is at

Tab. 1. The main physical and mechanical characteristics of loess soil

Tab. 1. Główne właściwości fizyczne i mechaniczne gleby lessowej

№	Soil density	Natural moisture	Density of the soil skeleton	Moisture at the yield point	Moisture on the verge of rolling	Plasticity number	Flow rate	Density of mineral particles	Porosity coefficient
	ρ_0,g/sm³	W_e ,p. units	ρ_d g/sm³	W_l , p. units	W_p , p. units	I_p	I_l	ρ_s g/sm³	e
1	1,55	0,137	1,36	0,24	0,20	0,04	≤0	2,63	0,934
2	1,77	0,143	1,55	0,26	0,22	0,04	≤ 0	2,68	0,729

Tab. 2. The component composition of low-density explosives and igdanite [2]

Tab. 2. Skład materiałów wybuchowych małej gęstości i igdanitu [2]

№	Explosives component	Igdanite	Low-density explosives
1	Ammonium nitrate	94,5	90
2	Diesel fuel	5,5	–
3	Sulfonal - powder	–	6
4	Aluminum powder	–	4

a distance of up to 10 radii of the charge or more. At the same time, the sharp nature of the pulse leads to an extremely fast dissipation of the wave energy, while the impact of the charge in space is rather uneven. This is characteristic of most industrial explosives with a stationary detonation rate of more than 3.5–4 km/s.

Therefore, the urgent problem is to change the parameters of the pulse to reduce unnecessary energy losses in the explosive zone as much as possible and increasing the radius of propagation by the action of one charge.

No less important is the problem of the optimal location of the wells in the massif, which allows choosing the deceleration parameters that provide the necessary blasting mode to achieve the maximum effect of using the energy of the explosion.

In addition, an important factor under the conditions of real soil massifs is the heterogeneity of their geological structure and physical and mechanical characteristics. This heterogeneity is especially evident in the upper layers of soil sediments, where the original layered structure of the massif, related to its geological origin, is often observed. However, if the object of engineering activity is a loess subsidence massif, its composition is more uniform in depth with a uniform increase in density or a decrease in porosity in the natural setting. The situation changes in connection with the application of any technology of compaction of such an array. It involves pre-soaking it to destroy sufficiently strong natural bonds between blocks and aggregates composed of grant particles and interconnected by salt films that can dissolve under the influence of excessive moisture. Since this moisture is practically incompressible, it is forced to move relative to the soil skeleton under the action of stresses on and outside the force front. The rate of movement of soil particles and moisture is directly proportional to the rate of first shock and then blast waves. In turn, the rate of the shock wave is directly proportional to the rate of the detonation front in the charge, that is, to the energy of the explosive substance in the charge. Thus, the known inertia of the medium in the dynamic process of the development of deformations is strengthened due to the mutual movement of the components that makes up the soil, since the influence of the viscous component on the process of the development of volumetric deformations increases.

2. Mathematical simulation of the explosive impact on the soil mass with the use of low-density explosives

It is known from soil dynamics [1] that an inertial multicomponent soil medium with relatively weak structural connections requires a slower increase and decrease of the load during the passage of the stress wave for the full development of the deformation process in the dynamic mode. This places appropriate requirements on the parameters of the explosive impulse, which provides a sufficient load that lasts longer in time. The problem can be solved only by using explosives with the lowest possible detonation rate.

The solution to this issue can be implemented in the following ways:

1. Improvement of the chemical composition of explosives. Since almost all the main components of low-explosive explosives are currently known, the improvement of the component composition, depending on the specific goals, is carried out by introducing hydrophobic, catalytic, inert, quasi-inert (low-calorie) and other additives.
2. Treatment of the structure of explosives or the main component (saltpeter) in order to increase chemical activity, which is complicated by the small area of chemical contact in coarsely dispersed explosives. The aim is to increase the surface area and partial ionization. It can be achieved due to mechanical (including ultrasonic) processing, by irradiation with electromagnetic waves and charged particles.

At the current stage of development of means of mechanization of charging works, two ways of improving the characteristics of the pulse are of practical interest, namely: using thin outer shells made of inert material; with the use of intermediate fighters in long wells, which well perceive the impulse from the main weak explosives.

Tab. 3. Dynamic characteristics of mixed explosives [2]

Tab. 3. Charakterystyki dynamiczne mieszanek wybuchowych [2]

№	**Characteristics**	**Unit of measurement**	**Explosive**		
			Igdanite	**Foam explosive**	**Ultrasonically processed foamed explosive**
1	Density of explosives, ρ_0	g/sm^3	0,85	0,6	0,5
2	Detonation rate: *D*, open charge	10^{3}m/s	3450	1500	1500
3	Heat of explosion *Q*	kcal/kg	870	1500	1500
2	Brisance of explosives	10^{-3}m	15-20	9-11	9-11
4	Time of pressure rise in the pulse	10^{-6}s	30	43	48
5	Pressure on the wave front	10^{9}Pa	2,0	0.95	0,85
6	Rate of pressure increase	10^{14}Pa/s	0,5-0,8	0.22	0,18
7	Polytropy index, *N*		4.41	2.24	2.12
8	Isentrope indicator, γ		0,264	0,235	0,212

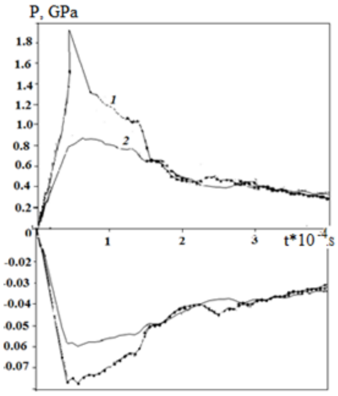


Fig. 1. Dependencies of average hydrostatic pressure and volume deformation of loess soil on time at the boundary with the explosive cavity during the explosion: 1 – igdanite, 2 – foamed explosives; 3 – foamed explosives, processed by ultrasound

Rys. 1. Zależności średniego ciśnienia hydrostatycznego i deformacji objętości gleby lessowej na granicy z wnęką wybuchową w czasie wybuchu: 1 – igdanit, 2 – spienione materiały wybuchowe; 3 – spienione materiały wybuchowe przetwarzane ultradźwiękami

In solving other problems, the determining factor is the mechanical properties of the surrounding mass: impedance, compressive strength, dilatancy, conditions of fragility, anisotropy, and heterogeneity.

In order to control the explosive impulse process, it is necessary to establish the following interrelationships: charging parameters, properties of the soil mass in the contact zone, and the initial parameters of the explosive impulse acting on the medium; mechanical properties of the array and wave parameters in the external medium; parameters of the external load on the soil massif.

On the basis of numerical experiments and theoretical research conducted in the last decade, it is established that in a number of typical conditions of detonation of explosive charges, the flow regime of the explosive transformation reaction is close to stationary, that is, the rate of propagation of the shock wave is close to constant.

The simplest quasi-stationary mode of detonation of a cylindrical charge is detonation with axial initiation, which generates a cylindrical wave.

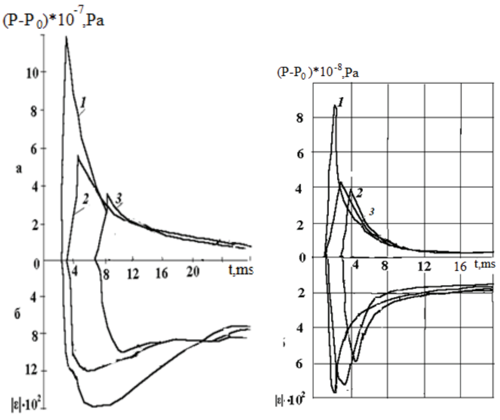
An increase in the volume concentration of the energy charge due to an increase in the density of explosives leads to an increase in the peak pressure of detonation, which in some cases reduces the efficiency of the energy of the explosive transformation due to a greater loss in the near zone of the explosion.

At research of the parameters of the explosive impulse for compaction of the territory of subsidence soils due to surface or horizontal cylindrical charges of explosives the limitation of explosive action of charges of explosives is required. This can be achieved by using low-density foamed explosive mixtures [2–3].

The analysis of previous studies when solving the problem of finding the radius zone of the base sealing around the well [4–6] with low-density foamed compositions demonstrates that it is necessary to determine the pressure at their contact "detonation products – medium". Based on numerous experimental data, the researchers believe that the efficiency of compaction of subsiding foundations when using an explosion is defined not only by the maximum pressure at the front of the detonation wave, but also by the duration of the explosive pulse. This occurs in the increase of the general form of the explosion at large distances from the charge, and, accordingly, in the improvement of the compaction of the grounded array at a considerable distance.

In this regard, it is necessary to study the relationship between the effectiveness of explosives (igdanite) and the foamed explosive composition, both conventionally and after treatment with ultrasonic irradiation, for the compaction of subsiding water-saturated soils with the maximum pressure, duration and shape of the explosive impulse that occurs at the boundary "products of detonation – medium".

Let's perform a numerical simulation of the camouflage effect of explosions of cylindrical charges of standard and new mixed explosives. Let a cylindrical explosive charge of infinite length and radius is placed in the soil space at a distance from the surface . Let the charge detonates instantly and the same average pressure is established throughout its volume , and the density of the explosion products is equal to the initial density of the explosive substance. The movement of soil explosion products is described by the laws of conservation of momentum, mass and internal energy, which for the explosion of a cylindrical charge have the form [7–8]:



a) b)

Fig. 2. Dependences of the average hydrostatic pressure (a) and volumetric deformation (b) of the medium on time in loam No. 1 and No. 2 at a relative distance r =5,5 r₀ at explosions of charges of various explosive substances: 1 – igdanite, 2 – foamed explosive; 3 – foamed explosive processed by ultrasound

Rys. 2. Zależności średniego ciśnienia hydrostatycznego (a) i odkształcenia objętościowego (b) w czasie w ośrodku ilastym nr 1 i nr 2 przy względnej odległości r =5,5 r₀ przy wybuchach ładunków różnych substancji wybuchowych: 1 – igdanit, 2 – spieniony materiał wybuchowy; 3 – spieniony materiał wybuchowy przetwarzany ultradźwiękami

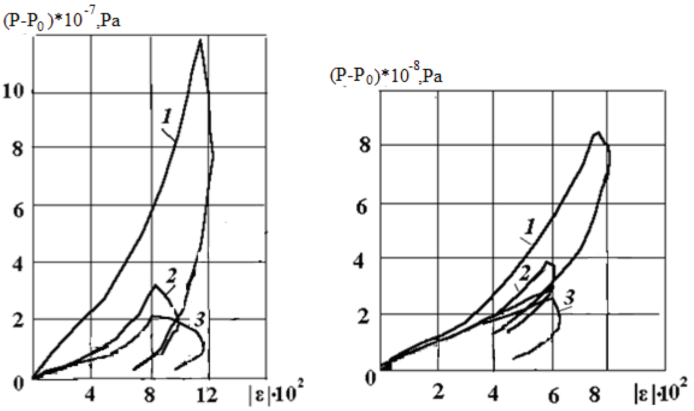


Fig. 3. Compression diagrams at loading and unloading in loam No. 1 and No. 2 at a relative distance r =5,5 r0 at explosions of charges of various explosive substances: 1 – igdanite, 2 – foamed explosive; 3 – foamed explosive processed by ultrasound

Rys. 3. Wykresy ściskania przy załadunku i rozładunku w iłach nr 1 i nr 2 na odległość względną r = 5,5 r0 przy wybuchach ładunków różnych substancji wybuchowych: 1 – igdanit, 2 – spieniony materiał wybuchowy; 3 – spieniony materiał wybuchowy przetwarzany ultradźwiękami

$$\frac{\partial \sigma_{rr}}{\partial z} + \frac{\partial \tau_{rz}}{\partial r} + \frac{\tau_{rz}}{r} = \rho \frac{du}{dt}, \tag{1}$$

$$\frac{\partial \tau_{rz}}{\partial z} + \frac{\partial \sigma_{zz}}{\partial r} + \frac{\sigma_{zz} - \sigma_{\theta\theta}}{r} = \rho \frac{dw}{dt}, \tag{2}$$

$$\frac{1}{V}\frac{dV}{dt} = \frac{\partial u}{\partial z} + \frac{\partial w}{\partial r} + \frac{w}{r}, V = \frac{\rho_0}{\rho}, \tag{3}$$

$$u = \frac{dz}{dt}, w = \frac{dr}{dt}, \tag{4}$$

$$\sigma_{zz} = S_{zz} - P, \sigma_{rr} = S_{rr} - P, \quad \sigma_{rr} = S_{rr} - P, \tag{5}$$

$$P = \frac{1}{3}\left(\sigma_{rr} + \sigma_{\theta\theta} + \sigma_{zz}\right), \tag{6}$$

Where ρ₀, ρ – initial and current density; u, w – rate tensor components; t – time; P –average hydrostatic pressure; r, θ, z – cylindrical coordinates; σ_i, S_i,(rr, θθ, zz) – tensor and deviator components of the stress tensor; $\overline{V}$ = V/V₀, V, V₀ – relative, current and initial specific volumes. For detonation products S_i=0. The relations are performed for the components of the strain rate tensor:

$$\dot{\varepsilon}_r = \frac{\partial U}{\partial r}, \quad \dot{\varepsilon}_\theta = \frac{U}{r}, \quad \dot{\varepsilon}_z = 0. \tag{7}$$

The expansion of the explosion products occurs according to the binomial is entropy, i.e

$$P = A\rho^{n_0} + B\rho^{\gamma_0 + 1} \tag{8}$$

The constant values A, B, n₀, γ₀in ratio (8) are calculated unambiguously based on the known characteristics of explosives [9].

The soil is simulated as a solid porous multicomponent medium with a variable coefficient of bulk viscosity η(ε) . The equations of loading and unloading of this medium have the form [10]:

$$\varepsilon = \varphi(P,\varepsilon)\dot{P} - \frac{\alpha_1 \lambda(P,\varepsilon)}{\eta(P,\varepsilon)}\psi(P,\varepsilon). \tag{9}$$

The functions included in equation (9) for loading and unloading are determined according to [12], where ε – volumetric deformation.

The condition of soil plasticity is the Mises-Botkin condition.

The initial conditions for this task are:

$$U = 0, P = P_{cp}, \ \rho = \rho_{BP} \text{ at } 0 \le r \le r_0,$$

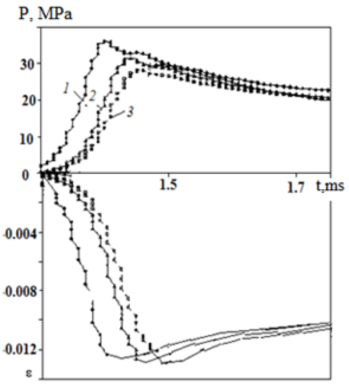


Fig. 4. Dependences of the average hydrostatic pressure (a) and volume deformation (b) on time in loam No.1 at a relative distance = 25.3:
1 – igdanite, 2 – foamed explosives; 3 – foamed explosive processed by ultrasound
Rys. 4. Zależności średniego ciśnienia hydrostatycznego (a) i odkształcenia objętościowego (b) od czasu w glinie nr 1 w odległości względnej = 25,3:
1 – igdanit, 2 – spienione materiały wybuchowe; 3 – spieniony materiał wybuchowy przetwarzany ultradźwiękami

$$P = \sigma_r = \sigma_\theta = \sigma_z = 0, \quad \rho = \rho_0 \text{ at } r > r_0 \tag{10}$$

where ρ_{BP}– initial density of the explosive.

The limiting conditions are:

1) the condition of continuity of rate and stresses at the boundary between the explosion product and the soil;

2) the condition of "no flow", i.e., the rate on the axis of the charge is zero.

To approximate the system of differential equations (1)–(10), the finite difference method applying the finite difference scheme of the "cross" type [10, 11] of the second order accuracy in spatial and temporal coordinates is used. A moving grid that automatically expands as the shock wave propagates is used at the solution. As an additional term to the average hydrostatic pressure in the differential equation of motion, a linear-quadratic artificial viscosity qis introduced, which allows conducting through-flow calculations, both on smooth and discontinuous flows.

Calculations are made for loess loams with the following physical and mechanical characteristics (Table 1).

Angle of internal friction (φ, degrees) – 19, specific adhesion (c, MPa) – 0.043, modulus of deformation (E, MPa) – 6.48 in the natural state and 2.41 in the water-saturated state, Poisson's ratio (μ) – 0,35.

An explosion of a charge with a radius r0= 0,09m is considered.

The component composition of low-density explosives and igdaniteis presented in Table 2, and their dynamic characteristics are in Table 3 (calculated according to the method [2–3].

Figure 1 presents the dependences of the average hydrostatic pressure and volumetric deformation of loam at the boundary with an explosive cavity during the explosion of igdanite (1) and foamed explosive (2).

It is demonstrated at the figure that at the border with the cavity during the explosion of the igdanite charge, significantly higher values of hydrostatic pressure and maximum volume deformation are achieved than during the explosion of the foamed explosives. It can be explained by the higher detonation characteristics of igdanite: density, pressure at the Juguet point. The time to reach the maximum pressure and deformation during an igdanite explosion is much shorter, because the detonation rate of igdanite is higher than that of foamed explosives.

Figure 2 demonstrates the dependences of the average hydrostatic pressure (a) and volume strain (b) in loams No. 1 and No. 2 at a relative distance r =5,5 r₀.

Analysis of these figures demonstrates that the nature of the dependence of pressure and maximum volumetric strain at the corresponding distance from time is the same as at the boundary with the explosive cavity: the greater the values of the detonation characteristics of explosives, the higher the values of pressure and volumetric strain.

From the comparison of the dependences for soils No. 1 and No. 2, it can be concluded that at the same distance from the explosive cavity in the first loam, lower pressures are achieved, but larger volume deformations. It is explained by the fact that the first soil has a lower density and higher volumetric porosity, therefore it is more contactable, and this in turn leads to larger deformations even at lower values of hydrostatic pressure. An increase in the porosity of the soil mass leads to a faster transformation of the shock wave into a continuous compression wave.

The same regularities are presented in Figure 3, which demonstrates compression diagrams during loading and unloading in loams No. 1 and No. 2. The explosion of the igdanite charge achieves significantly higher values of hydrostatic pressure and maximum volumetric strain than the explosion of foamed explosive and foamed explosive processed by ultrasound.

However it should be noted that the largest residual deformation is achieved in the case of explosions of foamed explosives compared to the explosion of igdanite. In addition, in the case of the explosion of the foamed explosive processed by ultrasound, the residual deformation is 9–10% greater than in the case of the explosion of the charge of the foamed explosives, not processed by ultrasound. This is due to the fact that the time of rise and fall of the pressure pulse of foamed explosives is on 13...18 mks longer than that of igdanite, which leads to a more complete transfer of energy from the explosion products to the soil.

Figure 4 shows the dependence of the average hydrostatic pressure and volume strain on time in loam No. 1 at a relative distance of 25.3. From the analysis of the figure, it is demonstrated that with distance from the center of the explosion, the difference in pressure maxima decreases and amounts to 16...21%, and the difference in initial pressures is 110...120%. This is because although igdanite has a higher density and initial pressure, foamed explosives have a higher heat of explosion.

In addition, the index of polytropy in igdanite is also higher, and this leads to a faster attenuation of the shock wave.

It can be noted that at this distance, not only the residual, but also the maximum volumetric deformations are greater in the case of foamed explosive explosions than in the case of an igdanite explosion. The difference in the maximum volume deformations during explosions of igdanite is 7...15% compared to explosions of ultrasonically foamed and ultrasonically processed, respectively.

It is interesting to note the result obtained by numerical calculations, which consists in the fact that at distances greater than 40, the greatest pressure and volume deformations are achieved during explosions of foamed explosives.

This allows us to make a conclusion about the advantages of using foamed explosives for the compaction of subsiding soils in comparison with traditional ones, because when they are used, thanks to a more complete transfer of the energy of the explosion to the soil mass, more uniform deformations are achieved over the entire interval from the source of the explosion to significant distances from it.

3. Conclusion

1. An inertial multicomponent soil medium with relatively weak structural connections requires a slower increase and decrease of the load during the passage of the stress wave for the full development of the deformation process in the dynamic mode. This leads to the appropriate requirements to the parameters of the explosive impulse, which provides a sufficient load that lasts longer in time. The greatest efficiency in the compaction of subsiding soils can be achieved when using a foamed explosive due to the action of the explosion at a considerable distance from the charge, and accordingly, uniform and better compaction to the required depth.

2. A mathematical formulation of the problem is made and an algorithm for calculating shock wave parameters in detonation products and soils during explosions of cylindrical charges of various industrial explosives is developed.

3. The dependences of the maximum pressure on the front of the detonation wave for different types of explosives on time and distance are obtained, which indicates that the lowest peak pressure at the longest duration of the explosive pulse is observed for charges based on foamed types of explosives, both conventional and processed ultrasonic radiation. The maximum pressure of these types of explosives is 20–49% less, and the duration of the explosive impulse is in 3–3.5 times longer compared to the standard low-density explosive – igdanite. The low value of the peak detonation pressure, achieved by reducing the density of explosives, reduces the volume concentration of the energy of the charges, which, in turn, increases the efficiency of the explosive transformation energy in the far zone.

4. The growth time of the explosive impulse of charges based on foamed explosives, both conventional and processed by ultrasonic radiation, is in 2.47 times greater than for igdanite.

5. It is established that in the near zone during the explosion of an igdanite charge, significantly higher values of hydrostatic pressure and maximum volume deformation are achieved than during the explosion of a foamed explosive. This is explained by the higher detonation characteristics of igdanite: density, pressure at the Juguet point. The time to reach the maximum pressure and deformation during an igdanite explosion is much shorter, because the detonation rate of igdanite is higher than that of foamed explosives.

6. Parameters of shock waves during explosions of charges of new mixed explosives in the middle zone can be compared with the same parameters from traditional industrial explosives, such as igdanite, and in the far zone of the explosion, they exceed them. The difference in the maximum volumetric deformations in igdanite explosions is 7–15% compared to the explosions of foamed explosive and foamed explosive processed by ultrasound, respectively. When detonating a sonicated foamed explosive, the residual deformation is 9–10% greater than when detonating a non-sonicated foamed explosive charge.

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Zarządzanie parametrami oddziaływania materiału wybuchowego na masę gleby w wyniku użycia materiałów wybuchowych małej gęstości

Na podstawie obliczeń numerycznych problemu wybuchu cylindrycznych ładunków substancji wybuchowych w glebach uzyskuje się zależności maksymalnego ciśnienia, odkształceń maksymalnych i szczątkowych dla różnych rodzajów substancji wybuchowych w czasie i odległości. Stwierdzono, że najniższe ciśnienie szczytowe przy najdłuższym czasie trwania impulsu wybuchowego obserwuje się dla ładunków opartych na materiałach wybuchowych spienionych, zarówno konwencjonalnych, jak i poddanych działaniu promieniowania ultradźwiękowego. Maksymalne ciśnienie tego typu materiałów wybuchowych jest o 20–49% mniejsze, a czas trwania impulsu wybuchowego jest 3–3,5 razy dłuższy niż w przypadku standardowego materiału wybuchowego małej gęstości – igdanitu. Niska wartość szczytowego ciśnienia detonacji, osiągnięta poprzez zmniejszenie gęstości MW, zmniejsza koncentrację objętościową energii ładunków, co z kolei zwiększa efektywność energii przemiany MW w strefie dalekiej. Czas narastania impulsu wybuchowego ładunków na bazie spienionych materiałów wybuchowych, zarówno konwencjonalnych, jak i poddanych działaniu promieniowania ultradźwiękowego, jest 2,47 razy większy niż dla igdanitu. Stwierdzono, że w strefie bliskiej podczas wybuchu ładunku igdanitu osiągane są znacznie wyższe wartości ciśnienia hydrostatycznego i maksymalnego odkształcenia objętościowego niż w przypadku wybuchu spienionego materiału wybuchowego, co jest konsekwencją wyższych charakterystyk detonacyjnych igdanitu: gęstości, ciśnienia w punkcie Jougeta, szybkości detonacji. Czas do osiągnięcia maksymalnego ciśnienia i odkształcenia podczas wybuchu igdanitu jest znacznie krótszy, ponieważ szybkość detonacji igdanitu jest większa niż w przypadku spienionych materiałów wybuchowych. Parametry fal uderzeniowych podczas wybuchów ładunków nowych mieszanek MW w środkowej strefie można porównać z parametrami tradycyjnych przemysłowych MW, takich jak igdanit, a w dalszej strefie wybuchu przewyższają je. Różnica w maksymalnych odkształceniach objętościowych w wybuchach igdanitu wynosi 7–15% w porównaniu odpowiednio do wybuchów spienionego materiału wybuchowego i spienionego materiału wybuchowego poddanego działaniu ultradźwięków. Podczas detonacji spienionego ładunku wybuchowego poddanego działaniu dźwięku, deformacja szczątkowa jest o 9–10% większa niż podczas detonacji spienionego ładunku wybuchowego nie poddanego działaniu dźwięku

Słowa kluczowe: *mieszanki wybuchowe, gleby osiadające, symulacje matematyczne*