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***Research paper***

# Efficiency of Using Explosive Foam Compositions for Compacting Structurally Unstable Soil

**Viktor Boiko**1), **Viktor Kravets**2), **Olena Han**2), **Anatolii Han**2), **Roman Zakusylo**3,*)

1) *Research Laboratory for Problems of Seismic Safety of Technological Explosions, Institute of Hydromechanics of the National Academy of Sciences of Ukraine, Kyiv, Ukraine*
2) *Department of Geoengineering, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Kyiv, Ukraine*
3) *Shostka Institute of Sumy State University, Shostka, Ukraine*
* *E-mail: r.zakusylo@ishostka.sumdu.edu.ua*

**ORCID information:**
Boiko V.: https://orcid.org/0000-0003-3443-1688
Kravets V.: https://orcid.org/0000-0002-5231-0778
Han O.: https://orcid.org/0000-0003-0739-9600
Han A.: https://orcid.org/0000-0003-0832-1338
Zakusylo R.: https://orcid.org/0000-0003-3823-4040

**Abstract:** The effectiveness of using improved low-density foamed explosive compositions with controlled explosive parameters for compacting structurally unstable loose soil has been theoretically substantiated and practically confirmed. Regularities in the distribution of the degree of soil compaction by explosive charges of industrial explosives and low-density local explosives, including foamed explosive compositions based on ammonium nitrate (AN) and treated with ultrasonic irradiation, have been established. This study addresses the current problem of scientific justification and practical implementation of the technological method for compacting structurally unstable loose soil.

**Keywords:** explosive impulse, volumetric energy concentration, foamed explosives, inclined boreholes

## 1 Introduction

In recent years, significant attention has been given to the application of economically competitive mixed explosives, with low detonation velocities, particularly those suitable for methods requiring consideration of not only the acoustic characteristics of interacting media in dynamic regimes, but also the temporal parameters of the process of transmitting the impulsive force to a passive medium. Numerical studies [1-8] have indicated that the reaction of deformed rocks to the initial mechanical impulse depends on their physico-mechanical properties and structural characteristics. The efficiency of the destructive action of an explosive impulse, *i.e.* the intensity of rock deformation, is closely related not only to the parameters of the explosive impulse (maximum pressure at the wavefront and its duration in the medium) but also to the relationship between these parameters. Any rock mass is characterized by varying degrees of inertial response to the impulse, and often requires a pressure at the front that is not as high as the prolonged dynamic load over time. This is less applicable to brittle strong rocks and more applicable to rocks with signs of viscosity. Increasing the volumetric energy concentration of the charge by increasing the density of the explosive leads to an increase in the peak detonation pressure, which, in some cases, reduces the energy utilization efficiency of the explosive transformation due to significant losses in the near field of the explosion [3].

When investigating the parameters of the explosive impulse for compacting structurally unstable soil territory using surface solid or distributed horizontal cylindrical charges of explosives, limitations on the brisance effect are required. This can be achieved by using low-density explosive mixtures, foamed explosive compositions, especially when treated with ultrasonic irradiation [1]. Analysis of previous studies on determining the radius of the soil compaction zone around a borehole using low-density foamed compositions [5, 6] showed the need to determine the pressure at the “detonation products - medium” contact.

Based on numerous experimental data, researchers believe that the effectiveness of compacting structurally unstable soil with explosives is determined not only by the maximum pressure at the detonation wavefront but also by the duration of the explosive impulse. This is manifested in the increase of overall work forms of the explosion at significant distances from the charge, resulting in improved compaction of the soil mass at considerable distances.

The objective of this study was to investigate the effectiveness of mixed explosives (ammonium nitrate (AN)-fuel oil (ANFO)) and foamed blasting compositions (FBC), both ordinary and after ultrasonic treatment (FBC+UST), for compacting settlement-prone soil using an explosively effective impulse shape, *i.e.* with moderate pressure and maximum duration of action, occurring at the "detonation products - medium" boundary.

## 2 Theoretical Background

Calculations of the explosive impulse for standard explosives (ANFO, ammonite), as well as foamed blasting compositions and FBC+UST, were performed using the methodology developed in [1-4]. The occurrence of the detonation wave at the interface between the detonation products and the surrounding medium gives rise to a shock wave, whose initial pressure is determined through the resolution of a system of equations (Equation 1).

$$\begin{cases} U_\text{H} = \sqrt{(P_{max} - P_0)\cdot(v_0 - v)} & \\ P_{max} = B\left[\left(\frac{\rho}{\rho_0}\right)^n - 1\right] & \\ U_\text{H} = \frac{D}{k+1}\left(1 - \sqrt{2k}\,\frac{\frac{p_{max}}{2Pcp} - 1}{\sqrt{(k+1)\frac{P_{max}}{2Pcp} + (k-1)}}\right) & \text{when } P_{max} > P_\text{cp} \\ U_\text{H} = \frac{D}{k+1}\left\{1 + \frac{2k}{k-1}\left[1 - \left(\frac{P_{max}}{2Pcp}\right)^{\frac{k-1}{2k}}\right]\right\} & \text{when } P_{max} < 2P_\text{cp} \end{cases} \tag{1}$$

where $U_\text{H}$ is the initial radial mass velocity of the shock wave at the boundary "detonation products - environment" (in m/s), $P_{max}$ is the initial pressure at the shock wave front, $v_0$ is the specific volume of the undisturbed environment ($v_0 = 1/\rho_0$), $v$ is the specific volume of the medium at the front of the shock wave ($v = 1/\rho$), $D$ is the detonation velocity, $P_\text{cp}$ is the pressure in the well under the conditions of instantaneous detonation and $n$ is an experimental coefficient that depends on the properties of the medium.

$$P_{cp} = (k-1)\rho_0{}'Q_v \tag{2}$$

where $Q_v$ is the heat of explosion per unit mass of explosive material ($Q_v = 427 \cdot Q \cdot q$, where $Q$ is the heat of the explosion and $q$ is the conversion index from kg to N ($q = 9.81$ N·m$^2$)) and $k$ is the isoentropy index in the overcompacted state of the detonation products ($k = 3$).

$$B = \rho c^2/n \tag{3}$$

where $\rho$ is the density of the environment and $c$ is the speed of the blast shock wave.

In the context of an actual detonation, the pressure at the interface "detonation products - surroundings" is characterized by the following relationships (Equation 4).

$$\begin{aligned}
P_r &= \left(\frac{r_0}{r}\right)^6 \left[\left(P_{max}\frac{r'''-r}{r''-r_0}\right) + P_{min}\left(1-\frac{r'''-r}{r'''-r_0}\right)\right] && \text{when } r_0 < r < r''' \\
P_r &= \left(\frac{r_0}{r}\right)^6 \left[\left(P_{min}\frac{r''-r}{r''-r'''}\right) + P_{cep}\left(1-\frac{r''-r}{r''-r'''}\right)\right] && \text{when } r''' < r < r'' \\
P_r &= P_{cp}\left(\frac{r_0}{r}\right)^6 && \text{when } r'' < r < r' \\
P_r &= P'_r\left(\frac{r'}{r}\right)^{2\gamma} && \text{when } r > r'
\end{aligned} \tag{4}$$

where $r''$ is the position of the distribution limit at which the pressure due to equalization reaches a minimum, $r_0$ is the explosive charge radius, $r$ is the radius of the distribution boundary "detonation products - environment" and $\gamma$ is the indicator of the isoentropy of an ideal gas ($\gamma = 1.3$). The unknown indicators P, $r''$ and $r'''$ are determined from the ratios:

$$\begin{aligned}
P_{min} &= 1.4P_{cp} - 0.4P_{max} \\
r''' &= r_0\left(1 - K_1\frac{U_H}{D}\right) \\
r'' &= r_0\left(1 + K_2\frac{U_H}{D}\right)
\end{aligned} \tag{5}$$

where $K_1$ and $K_2$ are dimensionless coefficients and are equal to 0.6 and from 1.7 to 2.5, respectively.

The path from $r_0$ *to* $r'''$, the distribution limit will pass in time $t_1$:

$$t_1 = 0.64 r_0 / D \tag{6}$$

and the path $r''' - r''$, the distribution limit will pass in time $t_2$:

$$t_2 = \frac{1.2 r_0 + 2r''}{D} \tag{7}$$

The pressure $P_r$ will be:

– at time $t_1$:

$$P_r = P_{min} \left(\frac{r_0}{r'''}\right)^6 \tag{8}$$

– at time $t_2$:

$$P_r = P_{cp} \left(\frac{r_0}{r''}\right)^6 \tag{9}$$

– and $P_\mathrm{r} = P_\mathrm{max}$ at time $t = 0$.

The graph of the dependence $P_r$ on $t$ is approximated by Equation 10.

$$P = P_0 \mathrm{e}^{-\alpha t} \tag{10}$$

where $\alpha$ is the logarithmic decrement of attenuation, which depends on the properties of the environment. The coefficients $P_0$ and $\alpha$ are from Equations 11 and 12.

$$\begin{gathered} P = P_0 = P_{max} \quad \text{when } t=0 \\ P_r{}' = P_{min} \left(\frac{r_0}{r'''}\right)^6 \quad \text{when } t = t_1 \end{gathered} \tag{11}$$

$$\alpha = \frac{l_n P_{max} - l_n P_r'}{t_1} \tag{12}$$

The time of increase of the explosive pulse is determined by the formula:

$$\tau = \frac{0.4r_0}{{}^3/_4\,D} \tag{13}$$

Using the fundamental relationships provided above, calculations were performed to determine the parameters of the explosive impulse for various explosive materials resulting from the detonation of charges with a radius of 30 mm in sandstone. The key input data are presented in Table 1.

**Table 1.** Physical and dynamic characteristics of the various explosives

| Index | Explosives | | | |
|---|---|---|---|---|
| | Ammonite 6 | ANFO | FBC | FBC+ UST |
| The density of the explosive, $\rho_0$ [g/cm$^3$] | 0.8 | 0.8 | 0.6 | 0.5 |
| Detonation velocity, $D$ [m/s] | 3700 | 3450 | 1500 | |
| Heat of explosion, $Q$ [kcal/kg] | 1030 | 870 | 850 | 840 |
| Environmental density, $\rho$ [kg/m$^3$] | 2800 | | | |
| Speed of propagation of the shock wave, $c$ [m/s] | 4950 | | | |
| Explosive charge radius, $r_0$ [m] | 0.03-0.09 | | | |

As an example, the calculation of the parameters of the explosive impulse for Ammonite 6 is demonstrated:

– for Equation 2:

$$P_{cp} = (k-1)\rho_0{}'Q_v = (3-1)\cdot 800\cdot 427\cdot 1030\cdot 9.81 = 6.90\cdot 10^9 \text{ N/m}^2$$

– for Equation 4:

$$B = \rho c^2/n = 2800\cdot 4950^2/4 = 17.15\cdot 10^9 \text{ N/m}^2$$

Solving Equations 1-13 gives:

$$P_{\max} = 8.19\cdot 10^9 \text{ N/m}^2$$

$$U_H = 1370 \text{ m/s}$$

$$P_{\min} = 1.4P_{cep} - 0.4P_{\max} = 6.37\cdot 10^9 \text{ N/m}^2$$

$$t_1 = 0.64r_0/\mathrm{D} = 0.64\cdot 0.03/3700 = 5.1\cdot 10^{-6} \text{ s}$$

$$r''' = r_0\left(1 + K_1\frac{U}{D}\right) = 0.03\left(1 + 0.6\frac{1370}{3700}\right) = 0.0367\text{ mm}$$

$$r'' = r_0\left(1 + K_2\frac{U}{D}\right) = 0.03\left(1 + 2.1\frac{1370}{3700}\right) = 0.0533\text{ mm}$$

$$t_2 = (1.2r_0 + 2r'')/D = (1.2 \cdot 0.03 + 2 \cdot 0.053)/3700 = 3.84 \cdot 10^{-6}\text{ s}$$

when $t = 0$: $P_r = P_{max} = 8.19 \cdot 10^9$ N/m$^2$

when $t = t_1$: $P_r{}' = \left(\frac{r_0}{r'''}\right)^6 P_{min} = \left(\frac{0.03}{0.0367}\right)^6 \cdot 6.37 \cdot 10^9 = 1.9 \cdot 10^9$ N/m$^2$

when $t = t_2$: $P_r = \left(\frac{r_0}{r''}\right)^6 P_{cp} = \left(\frac{0.03}{0.0533}\right)^6 \cdot 6.89 \cdot 10^9 = 0.22 \cdot 10^9$ N/m$^2$

$$\alpha = \frac{l_n P_{max} - l_n P_r'}{t_1} = \frac{l_n(8.19 \cdot 10^9) - l_n(1.9 \cdot 10^9)}{(5.1 \cdot 10^{-6})} = 2.86 \cdot 10^5\text{ s}^{-1}$$

$$\tau = \frac{0.4r_0}{{}^3\!/_4\,D} = 4.3\ \mu\text{s}$$

The calculations based on this methodology for Ammonite 6 do not take into account the width of the chemical reaction zone, thus they cannot accurately describe the pressure buildup at the distribution boundary during the detonation of explosive materials with a wide reaction zone, such as Igdanite (a granular explosive, which is a mixture of smooth granular AN with diesel fuel) and foamed explosives. In these materials, the pressure increase at the distribution boundary occurs gradually, from zero to the maximum value over the time it takes for the detonation wave to traverse a region equal to the width of the chemical reaction zone.

The change in pressure at the distribution boundary is determined by Equation 14.

$$P_r = \frac{P'Dt}{b}\left(\frac{r_0}{r}\right)^{2k} \qquad \text{when } 0 < t < t' \tag{14}$$

where $P'$ is the initial pressure at the distribution boundary, determined by the methodology described above, $D$ is the detonation velocity, $t$ is the time, $b$ is the width of the chemical reaction zone, $r_0$ is the charge radius, $r$ is the borehole radius and $t'$ is the time to peak pressure. Considering this, the parameters of the explosive impulse at the distribution boundary were calculated for the detonation of ANFO charges and foamed explosives. Solving this problem within the time interval from 0 to $t'$ involved solving the following differential equation:

$$\frac{d\bar{U}}{dt} = \frac{2r(P_r - P_0) - 2\rho_0 c R \bar{U}}{\rho_0' \cdot r_0^2 + \rho_0 \left(R^2 - r_0^2\right)} \tag{15}$$

where Ū is the average velocity of the average mass, $P_0$ is the atmospheric pressure and $R$ is the radius of the shock wave front.

Based on the calculation results presented in Table 2, Figure 1 shows the graphical representation of the explosive impulses for Amonite 6, ANFO and FBC when detonating charges with a radius of 30 mm in subsided forest soils. Figure 2 presents the time to reach peak pressure for these explosives.

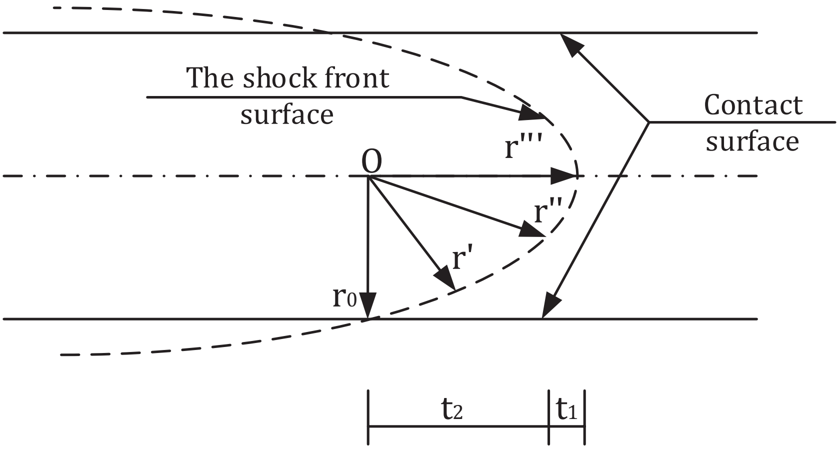

**Figure 1.** Calculation scheme (schematic diagram)

**Table 2.** Calculated parameters of explosive impulse for various explosive materials

| Parameter | Explosive material | | | |
|---|---|---|---|---|
| | Ammonite 6 | ANFO | FBC | FBC+ UST |
| Initial pressure at the front of the wave, $P_{max}\cdot 10^9$ [N/m$^2$] | 8.19 | 6.92 | 5.52 | 4.18 |
| The pressure in the well, under the condition of instantaneous detonation, $P_{cep}\cdot 10^9$ [N/m$^2$] | 6.89 | 5.82 | 4.27 | 3.25 |
| Minimum pressure, $P_{min}\cdot 10^9$ [N/m$^2$] | 6.37 | 5.38 | 3.77 | 3.26 |
| Pressure at time $t_1$, $P_r\cdot 10^9$ [N/m$^2$] | 1.9 | 1.76 | 0.31 | 0.4 |
| Pressure at time $t_2$, $P_r\cdot 10^9$ [N/m$^2$] | 0.22 | 0.24 | 0.009 | 0.016 |
| The passage time of the section from $r^0$ to $r'''$, $t_1$,$\cdot 10^{-6}$ [s] | 5.1 | 5.57 | 12.8 | |
| The passage time of the section from $r'''$ to $r''$, $t_2$,$\cdot 10^{-6}$ [s] | 38.5 | 39.94 | 135.4 | 122.3 |
| The growth time of the explosive pulse, [μs], when: | | | | |
| – $r_0$ = 0.03 m | 4.3 | 4.6 | 10.6 | |
| – $r_0$ = 0.06 m | 8.65 | 9.28 | 21.33 | |
| – $r_0$ = 0.09 m | 12.97 | 13.91 | 32.0 | |

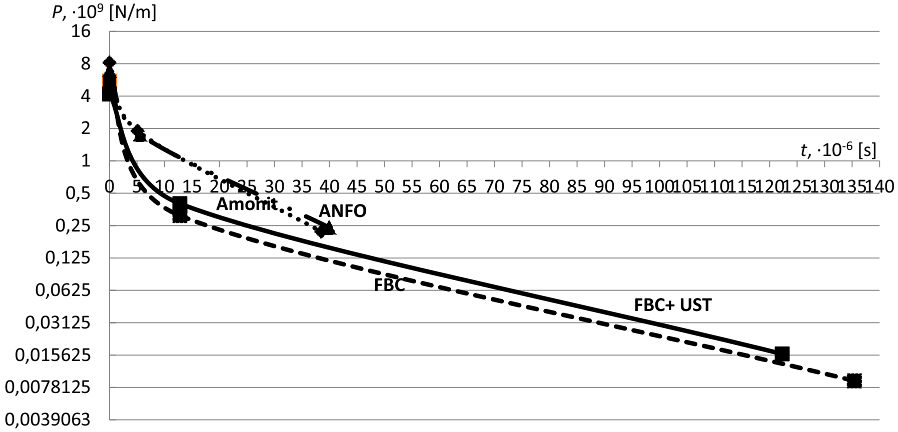

**Figure 2.** Pressure dependence at the "detonation products - surroundings" interface over time

As observed in Figure 2, charges based on foamed explosives exhibit a significant portion of the explosive impulse with a minimum peak pressure and maximum duration. Additionally, the pressure of the foamed explosive after ultrasonic treatment is slightly lower compared to the regular foamed explosive, but it has a longer duration of the explosive impulse.

A similar trend is observed when examining the duration of the explosive impulse growth. For both regular foamed explosives and those treated with ultrasonic radiation, the duration falls within the range of 10.6 to 32 µs. For ammonite, this parameter ranges from 4.3 to 12.97 µs, while for ANFO, it ranges from 4.6 to 13.91 µs (Figure 3).

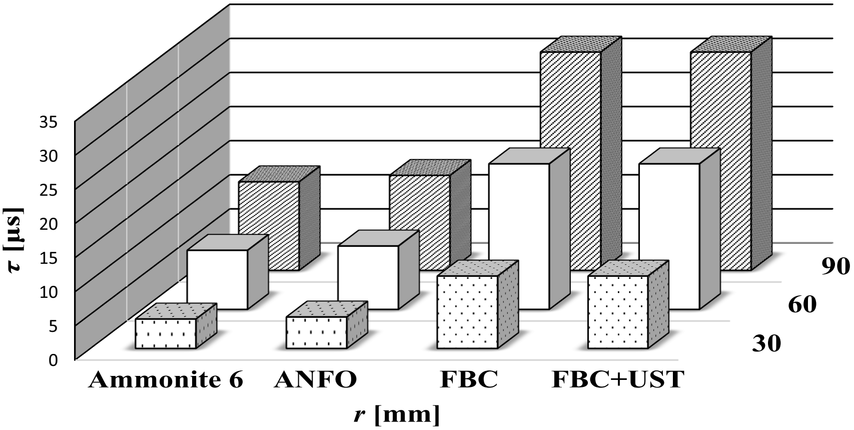

**Figure 3.** Dependence of the rise time of the explosive impulse on the radius of the explosive charge

The results of field studies and theoretical calculations indicate that the most effective compaction of subsidence-prone soils can be achieved by using foamed explosives, both conventional and treated with ultrasonic irradiation. These explosives, with minimal pressure at the “detonation products - surroundings” interface, have a significant duration of the explosive impulse, which should contribute to more uniform compaction of subsidence-prone soils throughout their depth. To confirm this conclusion, experimental research was conducted.

A well-known method of compacting such soils was applied, which involves the development of parallel trenches and drilling intersecting inclined boreholes at an angle of 30° to the vertical, placing linear charges of explosives in them, and detonating them (see Figure 4). The results of these field studies revealed patterns in the distribution of soil density with depth in its natural state and after explosive treatment. Figure 5 illustrates the influence of the type of explosive charge on the degree of soil compaction.

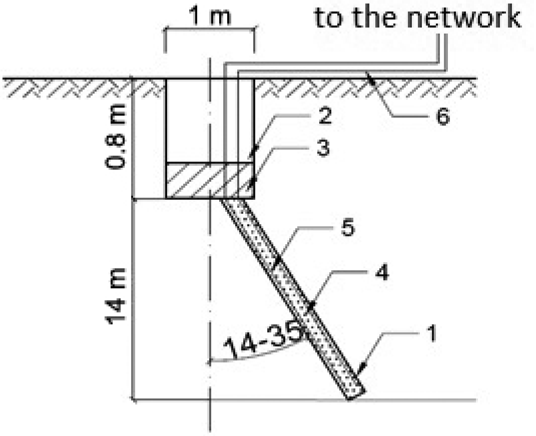

**Figure 4.** Diagram of soil compaction using the inclined charges system: 1 – well, 2 – trench, 3 – soil backfill, 4 – foamed explosive, 5 – detonation wave shaper and 6 – main pipeline

During this research, it was found that at a well inclination angle of 30° (Figure 4), a high soil density of (1.75-1.76) · $10^3$ kg/m³ was obtained when using a foamed explosive composition, including AN, which was pre-treated with ultrasound.

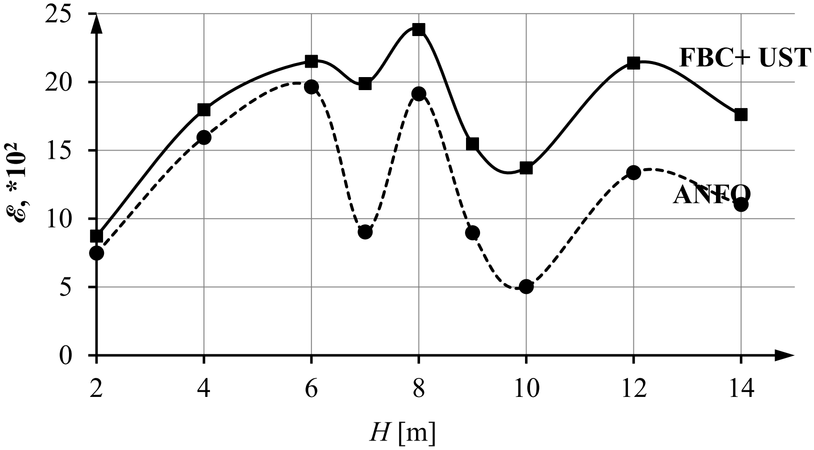

**Figure 5.** Dependence of soil compaction on the type of explosive charge

It is noted that some of the compaction results exhibit a pulsating nature, which can be attributed to the pronounced layered structure of the treated soil mass. This distinct layering leads to the reflection and refraction of the explosive waves between adjacent layers of the mass, resulting in corresponding deformation consequences. However, these consequences do not undermine the overall positive deformation effect that ensures reliable elimination of subsidence properties of the mass.

A more noticeable reduction in density in the subsoil mass (up to a depth of 4 m), regardless of the type of explosive charge, can be explained by the action of the charge's end portion in the loosening mode. This can be prevented by implementing appropriate charging parameter selection or employing known techniques for preparing the upper layer before the explosive treatment.

## 3 Conclusions

- The parameters of the explosive impulse at the "detonation products - surroundings" interface were determined for various types of explosive charge. A dependence between the maximum pressure on the detonation wave front of the explosive charge and the duration of the explosive impulse was obtained. It was found that the lowest peak pressure with the longest duration of the explosive impulse is observed for charges based on foamed explosives, both regular and those treated with ultrasonic radiation. The maximum pressure of these explosives is 20-49% lower, and the duration of the explosive impulse is 3-3.5 times longer compared to standard low-density explosives.
- The growth time of the explosive impulse for charges based on foamed explosives, both regular and those treated with ultrasonic radiation, is 2.3 times longer than for Ammonite 6 and 2.47 times longer than for ANFO.
- Analysis of the field research data obtained shows that the volumetric energy concentration in the charge cavity is lower when using low-density mixtures compared to standard explosives. However, the efficiency and effectiveness of compaction are higher in low-density mixtures. This can be explained by the redistribution of energy in the explosive impulse, achieved by reducing the peak pressure and increasing the overall duration of the compression phase. The latter allows for reduced energy losses in the near-field explosion zone due to unnecessary overcompaction of the soil.
- Control over the parameters of the explosive impulse using variable-density explosives enables uniform compaction of subsidence-prone forest soils to the required depth to be achieved by employing an inclined borehole charging system.

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