LITERATURE CITED

1. M. A. Sadovskii (ed.), Mechanical Effect of an Underground Explosion [in Russian], Nedra, Moscow (1971).
2. A. B. Bagdasaryan, "Analysis of the effect of an explosion in brittle mountain rock (destruction by crushing, formation of spall cracks and rupture)," Zh. Prikl. Mekh. Tekh. Fiz., No. 5 (1970).
3. S. Z. Dunin, O. V. Nagornov, and E. A. Popov, "Elastic wave emission in a camouflet explosion," Izv. Akad. Nauk SSSR, Fiz. Zemli, No. 2 (1982).
4. V. N. Nikolaevskii, K. S. Basniev, A. G. Gorbunov, and G. A. Zotov, Mechanics of Saturated Porous Media [in Russian], Nedra, Moscow (1970).
5. S. Z. Dunin and V. K. Sirotkin, "Expansion of a gas cavity in brittle rock with the dilatancy properties of the soil taken into account," Zh. Prikl. Mekh. Tekh. Fiz., No. 4 (1977).

BLAST WAVES IN FROZEN SOILS

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We present results of experimental studies of spherical blast waves in seasonally frozen soils with different physical and mechanical properties at different temperatures. A comparison with results in [1, 2] shows that the wave parameters depend strongly on the characteristics of the soil in the initial unfrozen state and on the temperature. When the temperature falls, the maximum stresses and the wave velocity increase, but the duration of the wave decreases. The general character of the extinction and flattening of waves in frozen soils, just as in unfrozen soils, is typical of media having plastic properties and bulk viscosity [2].

1. Characteristics of Soils and Test Conditions. Frozen soils are four-component media containing solid mineral particles forming the skeleton, unfrozen water, ice, and air. We denote the volume fractions of the components as follows: air (free interstitial space), α_1; water, α_2; mineral particles, α_3; ice, α_4 (α_4 is also called the volumetric iciness); ρ_1, ρ_2, ρ_3, ρ_4 are the densities of the corresponding components. These quantities are related to the density of the soil ρ_0, the mass (weight) moisture content w, and the gravimetric iciness i by the equations

$$\begin{gathered}\alpha_1+\alpha_2+\alpha_3+\alpha_4=1,\quad \alpha_1\rho_1+\alpha_2\rho_2+\alpha_3\rho_3+\alpha_4\rho_4=\rho_0,\\ \alpha_4\rho_4/(\alpha_2\rho_2+\alpha_4\rho_4)=i,\quad (\alpha_2\rho_2+\alpha_4\rho_4)/\alpha_3\rho_3=w.\end{gathered}\tag{1.1}$$

When the temperature falls the volume contents of the components change. This occurs as a result of possible migration of water from the lower layers of the soil to the frost front, and also as a result of the gradual freezing of the interstitial water [3, 4]. Therefore, the values of the quantities listed above must correspond to the temperature at which the experiments are performed and also to the initial (atmospheric) pressure.

The experiments were performed in sandy and loamy soils of natural structure under conditions of seasonal freezing to a depth of 0.45-0.5 m. The granulometric composition of the sandy soil is shown in Table 1.

At a soil temperature $t = -0.2°C$ the average values of the soil characteristics were: $\rho_0 = 1840$ kg/m³, $\rho_3 = 2660$ kg/m³, w = 0.27, i = 0.73.

The granulometric composition of the loamy soil is shown in Table 2.

In granulometric composition the soil falls into the category of loam, close to sandy loam. At temperatures −0.2°C and −0.4°C the average values of the characteristics of the components were: $\rho_0 = 1920$ kg/m³; $\rho_3 = 2680$ kg/m³; w = 0.22 in both cases; and i = 0.5 and 0.75, respectively.

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TABLE 1

Particle size mm	Contents of fractions, %
0,5	5
0,5—0,25	16
0,25—0,1	21,4
0,1	57,6

TABLE 2

Particle size mm	Contents of fractions, %
0,1—0,05	24
0,05—0,01	52
0,01—0,05	12
0,05	12

TABLE 3

Soil	t, °C	α_1	α_2	α_3	α_4
Sandy	—0,2	0,037	0,105	0,545	0,313
Loamy	—0,2	0,048	0,192	0,585	0,175
«	—0,4	0,038	0,087	0,586	0,289

TABLE 4

Soil	t, °C	$R=10$	$R=35$
Sandy	—0,2	2	4,5
Loamy	—0,2	2,7	4,7
»	—0,4	1,8	3,2
»	—3	19	23

Taking for the densities of the components $\rho_1 = 1.2$ kg/m^3, $\rho_2 = 1000$ kg/m^3, $\rho_4 = 910$ kg/m^3, we find the volume contents of the components from Eq. (1.1) (Table 3).

Unfrozen soils with these contents of the components are water-saturated; gas is contained in the form of bubbles, isolated from the atmosphere. With a decrease in α_1 the compressibility of water-saturated unfrozen soils is substantially decreased [2].

Stresses were measured with piezoceramic transducers having natural frequencies ω = 40,000 Hz, and the signals were recorded on electron oscillographs. Membrane transducers with ω = 4000 Hz were also used, with the signals recorded on loop oscillographs.

The transducers and the explosive charge were placed at the same depth in holes bored in frozen soil. The material removed in boring the holes was then replaced and tamped. The experiments were performed after the soil was frozen together. Waves were generated by the explosions of concentrated 0.1-kg charges. In sandy soil the depth of the transducers h = 0.4 m at t = −0.2°C; in loamy soil h = 0.2 m at t = −0.4°C, h = 0.35 m at t = −0.2°C, and h = 0.45 m at a temperature near zero. The last depth corresponded approximately to the frost line. The radial (σ_r) and tangential (σ_θ) stresses were measured at each distance. We used ammonite No. 6 liquid explosive with a density ρ = 1000 kg/m^3.

2. Experimental Results. We introduce the relative distance $R = r/r_0$, where r is the distance from the center of the explosion, and r_0 is the radius of the explosive charge. The transducers were placed at distances R from 10 to 35.

Figures 1a and 1b are samples of traces of the stress in frozen sandy soil at R = 13 and 20. The maximum stresses were 8 and 3.5 MPa. The distances between two adjacent vertical lines on the oscillograms (time scale) are 100 and 500 μsec, respectively.

It follows from the oscillograms shown, and from the others, that at the distances investigated $10 \le r \le 35$, which correspond to maximum values of $\sigma_r < 20$ MPa, the blast wave is not a shock. The stress increases to the maximum gradually. During the motion the time τ for the stress to rise to a maximum, and the total duration θ of the wave increase approximately linearly. At R = 10, τ = 0.1 msec and θ = 0.5 msec; at R = 35, τ = 1 msec and θ = 2.5 msec. In determining the values of τ and θ we counted the times when σ_r was not less than 0.02-0.03 of the maximum stress at that distance.

Curve 1c in Fig. 2 with experimental points represents the maximum values of the radial stress in frozen sandy soil $\sigma_r = \sigma_r(R)$. Curves 2 and 3 without experimental points are taken from [2]. They show the maximum stress $\sigma_r(R)$ in unfrozen sandy water-saturated soil of natural structure with the following content of the components: α_1 = 0.03-0.04, α_2 = 0.36-0.37, α_3 = 0.6; α_1 = 0.008-0.012, α_2 = 0.388-0.392, α_3 = 0.6, respectively, for underground explosion.

Curve 1 of Fig. 3 shows the dependence of the velocity of the wave front on distances $D_f(R)$. By the velocity of the front we mean the propagation velocity of the state of the wave with a stress σ_r = 0.02-0.03 of the maximum value. Curve 2 corresponds to the propagation velocity of the maximum stress in the wave $D_m(R)$. Both curves are for sandy soil at

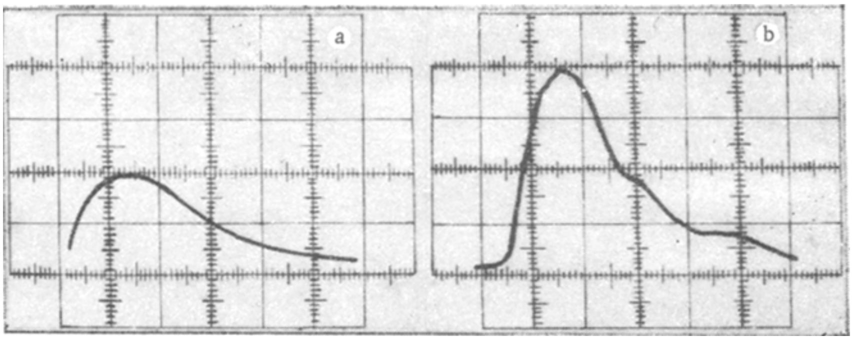

Fig. 1

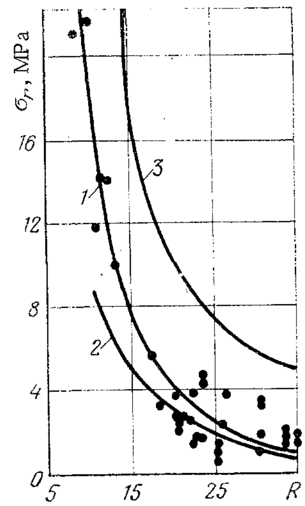

Fig. 2

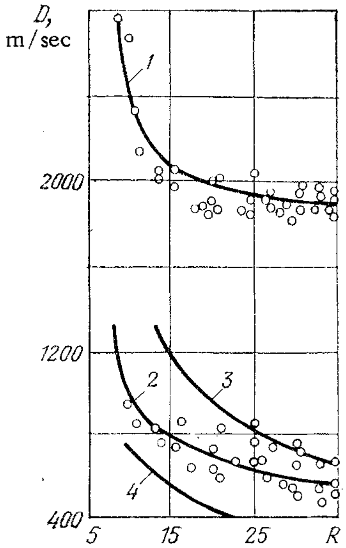

Fig. 3

a temperature $t = -0.2°C$. Curves 4 and 3 determine the propagation velocity of the maximum stress in unfrozen sandy water-saturated soil for $\alpha_1 = 0.03$-0.04 and $\alpha_1 = 0.008$-0.012, respectively [2].

A comparison of the curves in Figs. 2 and 3 shows that at a temperature $t = -0.2°C$ the maximum stresses $\sigma_r(R)$ and their propagation velocity $D_m(R)$ are higher than in unfrozen soil of approximately the same density and with approximately the same content of entrapped air. For $\alpha_1 = 0.01$ the stress $\sigma_r(R)$ and the velocity $D_m(R)$ in unfrozen soil are substantially higher than in frozen soil for $\alpha_1 = 0.035$. Thus, the cementing of mineral particles by ice at $t = -0.2°C$ and the decrease in compressibility of the soil which result from it lead to a smaller change of the wave parameters than the decrease in compressibility produced by the decrease of the content of entrapped air to 0.01 without a decrease in temperature. We note that the explosions in frozen soil were not underground, which can decrease the values of the stress and velocity.

Figures 4a and b show the dependence of the maximum radial and tangetial stresses on distance in loamy soil. Curves 1-3 of Fig. 4a are for temperatures of -0.4, -0.2, and 0°C, respectively. Curves 1 and 2 of Fig. 4b show the tangential stresses at $t = -0.4$ and $-0.2°C$. The curve for $t = 0°C$ is not shown; it lies 15-20% lower than curve 2. A comparison shows that a temperature drop in frozen soil leads to an increase in the radial and tangential stresses. For a change in temperature from 0 to $-0.2°C$ in the range of distances considered the stress increases by 20-50%, and for a change from -0.2 to $-0.4°C$ it increases by a factor of 4-5. This increase is related to the fact that the cementing of solid particles by ice increases with decreasing temperature more rapidly than linearly.

Curve 4 of Fig. 4a, taken from [2], represents the radial stresses during an explosion in unfrozen clay soil with $\rho_0 = 2000$-2100 kg/m³ and a gaseous content $\alpha_1 = 0.02$-0.03. A comparison of curves 1 and 4 shows that a decrease in temperature from 0 to $-0.4°C$ and the

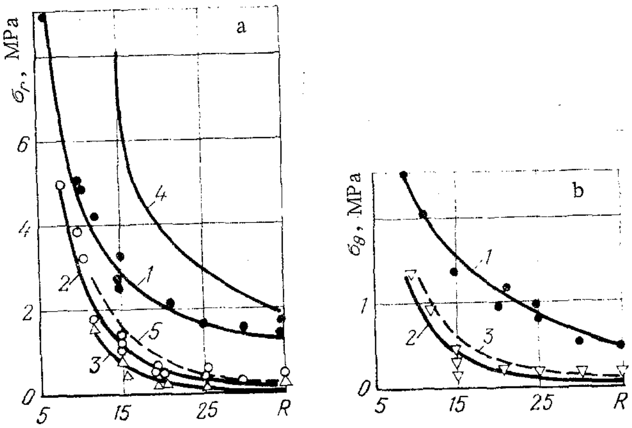

Fig. 4

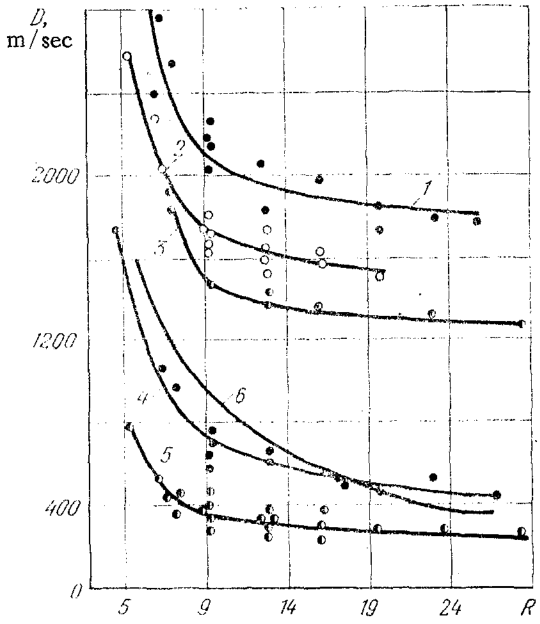

Fig. 5

accompanying cementation of particles by ice have a smaller effect on the compressibility of soil and the change in blast wave parameters resulting from it than a decrease in the content of entrapped air from 0.048 to 0.02-0.03 at a temperature above zero.

Curve 5 of Fig. 4a and curve 3 of Fig. 4b (without experimental points) represent the maximum radial and tangential stresses of a wave in loamy seasonally frozen soil with a granulometric composition close to that of the soil under consideration (expts. [1]). The contents of the components were as follows: $\alpha_1 = 0.14$, $\alpha_2 = 0.25$, $\alpha_3 = 0.61$, $\rho_0 = 1870$ kg/m^3. A soil with such characteristics in the unfrozen state is not water-saturated. The mass of the explosive charge was 0.025-0.075 kg, the depth of the charge and transducers was 0.25-0.30 m, and the soil temperature was -3°C. A comparison of curves 1 and 5 of Fig. 4a, and 1 and 3 of Fig. 4b shows that in unsaturated soil at -3°C the maximum stresses are substantially lower than in water-saturated soil at $t = -0.4$°C. Cementing of the mineral particles of unsaturated soil by ice leads to a smaller change of the wave parameters than an increase of moisture content to the saturated state for a substantially smaller temperature drop.

The tangential stresses in frozen soil (Fig. 4a, b) are appreciably smaller than the normal stresses, as in unfrozen soils.

Curves 1-3 of Fig. 5 show the propagation velocity of the wave front D_f, and curves 4 and 5 the propagation velocity of the maximum stress D_m in frozen loamy soil. Curves 1-3 are for temperatures -0.4, -0.2, and 0°C, respectively. A temperature drop leads to an increase in D_f and D_m. Near the explosive charge D_f and D_m decrease rapidly with distance, as in unfrozen soils; far from the charge both velocities decrease much more slowly. Curve 6 shows the velocity of propagation of the maximum stress in unfrozen water-saturated clay soil with $\rho_0 = 2000$-2100 kg/m^3 and $\alpha_1 = 0.02$-0.03 (data from [2]). The velocity D_m in soil with $\alpha_1 = 0.048$ at $t = -0.4$°C is substantially lower than in unfrozen soil with $\alpha_1 = 0.02$-0.03.

We denote by θ the duration of the effect of the wave. We introduce the relative time of the effect $\theta^\circ = \theta/\sqrt[3]{Q}$, where Q is the mass of the explosive charge. The experimental values of $\theta^\circ \cdot 10^3$ for two distances are listed in Table 4. For comparison the table includes the values of $\theta^\circ \cdot 10^3$ from [1] for unsaturated frozen loams at $t = -3$°C.

In all cases θ° varies approximately linearly with distance.

Thus, a comparison of the experimental data obtained with the results of earlier studies shows that the dynamic properties of frozen soils depend strongly on the granulometric composition, the content of the components in the original unfrozen state, and the temperature. In frozen water-saturated soils the stress and wave velocity are higher, but the duration of the wave is shorter than in frozen unsaturated soils.

As the temperature of frozen soils decreases, the amount of unfrozen interstitial water decreases, and the cementing of solid particles by ice increases, which leads to a decrease of the compressibility of the medium. The stress and wave velocity increase, but the duration of its effect decreases.

Experiments [4-6] showed that a temperature drop in frozen soils leads to an increase in the propagation velocity of longitudinal waves. Thus, the velocities of blast waves of finite amplitude and longitudinal waves vary the same way during the freezing of soil.

Experiments [7] show that the volume strains of frozen soils depend strongly on the rate of loading $\dot{\sigma}$. In media with such properties, blast waves are flattened — transformed from shock waves into continuous compression waves [2]. The dependence of strain on $\dot{\sigma}$ shows that the flattening of blast waves observed in experiments is related to bulk viscosity.

The experiments performed confirm that the basic laws of the extinction of waves in frozen and unfrozen soils have a common character:

The rate of decrease with distance of the wave amplitude (maximum stress) and its propagation velocity depend on the contents of the components; with an increase in moisture content, the rate of decrease diminishes;

the velocity of the wave front decreases more slowly with distance from the explosion than the velocity of the maximum stress;

the time for the stress to increase to a maximum, and the total duration of the wave increase as the wave propagates; the wave is flattened;

the normal and tangential stresses are very different;

remanent strains remain in the soil after passage of the wave. All these laws are characteristic of unfrozen soils also.

Both frozen and unfrozen soils should be considered as multicomponent solid media having plastic properties and bulk viscosity. Frozen soils differ from unfrozen in the quantitative manifestation of these properties and in the temperature dependence of the controlling physical and mechanical characteristics.

LITERATURE CITED

1. Yu. Ya. Trukhanov, "Experimental study of stress and particle velocity distributions in an explosion in frozen soil," Fiz. Goreniya Vzryva, No. 1 (1967).
2. G. M. Lyakhov, Fundamentals of the Dynamics of Blast Waves in Soils and Rocks [in Russian], Nedra, Moscow (1974).
3. N. A. Tsytovich, The Mechanics of Frozen Soils [in Russian], Vysshaya Shkola, Moscow (1973).
4. N. Z. Drogoveiko, Explosive Fracture of Frozen Soils [in Russian], Nedra, Moscow (1981).
5. A. D. Frolov, Electrical and Elastic Properties of Cryogenic Rocks [in Russian], Nedra, Moscow (1976).
6. N. E. Zarubin and V. I. Dzhurik, "Seismic properties of frozen soils of the Baikal region," Osn. Fundam. Mekh. Gruntov, No. 3 (1975).
7. A. A. Vovk, A. V. Mikhalyuk, et al., "Mechanical properties of frozen soils under dynamic loading," Osn. Fundam. Mekh. Gruntov, No. 2 (1980).