PARAMETERS OF CYLINDRICAL BLAST WAVES IN WATER-IMPREGNATED SANDY LOAM

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Experimental results are given on the parameters of cylindrical blast waves in water-impregnated sandy loam as a function of the charge depth, the distance from the charge, and the free porosity of the soil.

Experimental data have been published on the parameters of cylindrical and spherical blast waves in soils containing ambient moisture [1-4] and of spherical waves in water-impregnated sands [5, 6].

We now give the results of an experimental study of the parameters of blast waves from cylindrical charges in water-impregnated sandy loam at the water diminution level. The need for such a study has been dictated by the considerable number of technological problems using cylindrical high-explosive charges under soil conditions analogous to those in the present experiment. The granulometric composition of the soil is described below. The moisture content of the soil under natural impregnation conditions is 39 to 41% the volumetric density $\rho = 1.92$ g/cm^3, and the free porosity $\alpha_1 = 2.5 \cdot 10^{-2}$:

δ, mm	0.5—0.25	0.25—0.05	0.05—0.01	0.01—0.005	< 0.005
n, %	46.5	21.32	23.7	4.58	3.9

We used horizontal cylindrical TNT charges 5 m in length, which had the following weights per meter C and placement depths H:

C, kg/m	4.0	2.0	2.0	2.0	1.0	1.0	1.0	1.0
H, m	0.80	0.93	0.56	0.45	0.20	0.35	0.55	0.70

We also used vertical cylindrical charges 3 m in length with weights per unit length of 0.55, 1.0, and 1.4 kg/m.

The blast wave parameters were measured by the procedure of [2, 4] with the use of strain gauges, whose signals were amplified by an 8 ANCh (low-frequency) amplifier and recorded on a modified-design N-700 oscilloscope [1].

The strain gauges were implanted in the soil at calculated distances from the blast source in special boreholes 45 mm in diameter and were then covered over layer by layer with the original soil taken from the holes. The subsequently tamped and water-impregnated soil established continuous contact between the soil mass and the gauge diaphragm. The body of the gauge was filled with transformer oil to protect the measuring and current-carrying elements from the water. The oil-filled gauges were statistically calibrated in a hydraulic press just prior to their placement in the bore holes.

In recording the blast waves from a horizontal cylindrical charge the gauges were placed at the same depth as the charge along the perpendicular to its midpoint, and for a vertical cylindrical charge they were also placed along the perpendicular to it at the same depth as its midpoint.

The experimental data were processed by geometrical similitude principles, whereby the similar time, depth, and distance are chosen in the form

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$$t_-^\circ = \frac{10^3 t_-}{\sqrt{C}}, \quad t_+^\circ = \frac{10^3 t_+}{\sqrt{C}}, \quad H_+ = \frac{H}{\sqrt{C}}, \quad R_+ = \frac{R}{\sqrt{C}} \tag{1}$$

where t_- and t_+ are the times (msec) of arrival of the disturbance and of maximum stress at a given point, and R is the distance (m) from the charge to the measurement site.

All the experimental results are plotted below in appropriate coordinates with allowance for the scale effect in processing of the data by the method of least squares.

It has been shown experimentally [6] that a blast wave in completely water-saturated soil has a shock character at any distance from the blast source, i.e, as the wave front approaches a given point in the soil mass the pressure at the front jumps instantaneously to a finite value $\sigma = \sigma_+$ and then decays almost exponentially.

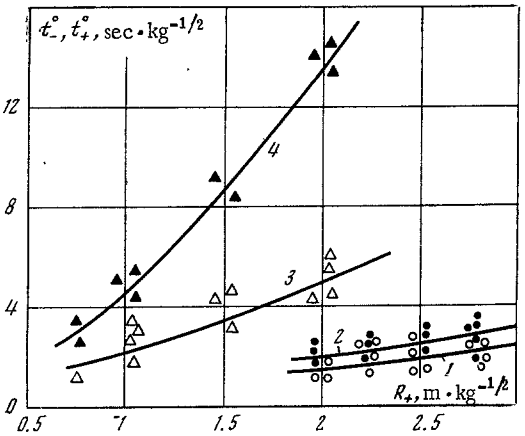

Fig. 1

For soil in the given physical state, upon denotation of a cylindrically symmetric charge in an unbounded medium, the stress intensity at the wave front decays with distance only as a result of geometrical spreading of the front without plastic deformation losses. Any departure of the wave damping from that just stated, like the decay of any blast wave front, i.e., the occurrence of a disparity in the propagation velocities of the wave front and the stress maximum, indicates energy losses in plastic deformation of the soil.

It has been established experimentally that with even a slight free porosity of the soil (less than 2% by volume), at certain distances from the blast source the wave front of the elastic disturbances will separate from the maximum-stress front, i.e., the blast wave will lose its shock character. The experimental curves in Fig. 1 characterize the arrival time at a given point in the soil mass of the wave fronts of the elastic disturbance (curve 1) and stress maximum (curve 2) in water-impregnated sandy loam, along with their counterparts in pure loam (curves 3 and 4), respectively, with an undisturbed density of 1.96 g/cm^3 and a volumetric moisture content of 14% in the detonation of a vertical cylindrical charge. The curves are described mathematically by a power law of the form

$$t_-^\circ,\ t_+^\circ = a_i R_-^{b_i} \tag{2}$$

The values of the coefficient a_i and power exponents b_i are as follows:

Impregnated sandy loam

a_1	a_2	a_5	a_6	b_1	b_2	b_5	b_6
1.15	1.15	1.16	1.24	1.0	1.12	1.0	1.1

Ambient moisture loam

a_3	a_4	a_7	a_8	b_3	b_4	b_7	b_8
2.59	4.74	3.06	4.54	1	1.58	1	1.19

The subscripts attached to the coefficients and exponents indicate the curve numbers in Fig. 1. The subscripts 5-8 refer to horizontal cylindrical charges in impregnated sandy loam (5, 6) and natural loam (7,8).

As the data of Fig. 1 show, along with the perceptible decay of the blast wave front for the given types of soils, a large disparity is also noted in the absolute values of t_- and t_+ in connection with the different moisture contents of the approximately equal-density soils.

The propagation speeds of the elastic front (D_-) and stress maximum (D_+) for a cylindrical blast wave in both types of soils as a function of the relative distance R_+ are satisfactorily described by equations of the form

$$D_-,\ D_+ = m_i R_+^{n_i} \tag{3}$$

The numerical values of the coefficients m_i and exponents n_i are as follows:

Impregnated sandy loam

m_1	m_2	m_5	m_6	n_1	n_2	n_5	n_6
870	850	265	730	0	0.12	0	0.1

Ambient moisture loam

m_3	m_4	m_7	m_8	n_3	n_4	n_7	n_8
386	193	340	185	0	0.58	0	0.19

The subscripts for the type of soil and type of charge are analogous to those used above.

Thus, in the range of relative distances from the blast source for the given curves, irrespective of the type of soil or its degree of impregnation, the blast wave front and maximum-stress fronts propagate at different speeds. It has been demonstrated experimentally, on the other hand, that for relative distances sufficiently close to a cylindrical charge ($R_+ < 0.1$), irrespective of the free porosity of the medium, a blast wave with a shock front propagates in it [7]. The distances at which the front decays, decreases as the free porosity increases and increases with the degree of impregnation of the soil.

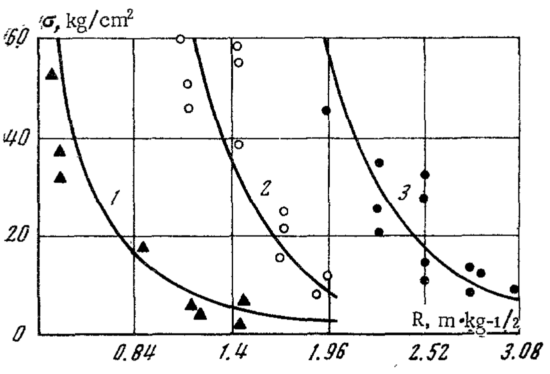

Fig. 2

The dependence of the increment σ_+ of the normal radial stresses at the blast wave front on the relative distance is shown in Fig. 2 for the detonation of vertical (curve 3) and horizontal (curve 2) charges in water-impregnated soil and for the detonation of a vertical cylindrical charge in the comparison loamy soil (curve 1). The decay of the stresses in the cylindrical blast waves is given by an equation of the form

$$\sigma_+ = k_i R_+^{-\mu_i} \qquad (4)$$

The numerical values of the coefficients k_i and exponents μ_i are as follows:

k_1	k_2	k_3	μ_1	μ_2	μ_3
9.75	1440	114.8	2.17	4.8	3.76

The subscripts correspond to the curve numbers in Fig. 2.

As Fig. 2 indicates, the damping of the blast wave from a horizontal cylindrical charge with distance for one given type of soil is more rapid than for a vertical cylindrical charge. This difference is explained by the influence of the free surface, in that the stress intensity at the wave front at equal relative distances from the blast source decreases with shallower placement of the charge relative to the free surface.

The variation of the stresses at the wave front at a certain distance ($R_+ = 1.96$) from horizontal cylindrical charges placed at different depths in water-impregnated soil is shown in Fig. 3. It is seen that the stresses increase insignificantly as the relative depth is increased within the interval $H_+ < 0.45$; in the interval $0.45 \leq H_+ \leq 0.75$ the maximum stress at the wave front is seen to increase sharply; for $H_+ > 0.75$ the original dependence is observed, i.e., a further increase in the placement depth of the charge yields only a slight increase in the stresses, which tend in the limit to a definite value characteristic of the given soil type, its initial physical constants, and the relative distance from the blast source.

The depth $H_+ = 0.75$ is the minimum placement depth for a horizontal cylindrical high-explosive charge, characterizing the optimum regime for the transfer of explosive's energy into the blast wave.

Sufficiently long vertical cylindrical charges detonated under typical undergound conditions are similar to horizontal cylindrical charges placed at the depth $H_+ = 0.75$. The rate of damping of the blast waves from such charges in one type of soil is therefore roughly the same. For a shallower placement depth relative to the free surface the intensity of the blast waves from horizontal cylindrical charges at equal relative distances is lower than for vertical cylindrical charges.

It follows from a comparison of curves 1 and 3 in Fig. 2 that for different moisture contents and different structural bonds in the soil the maximum stresses at the blast wave front at identical relative distances from the blast source can vary by an order of magnitude or more.

The samping of the blast wave intensity is a function of the energy spent in volume deformation of the given type of soil. At the blast wave front a local microdeformation of the soil takes place, which is felt in a constriction of the air-filled free pores and in a breakdown of the rigid cementation bonds and force field associated with interaction of the water strata. The energy losses and intensity decay at the blast wave front therefore depend on the moisture content of the soil, i.e., on how highly developed are the indicated types of structural bonds therein.

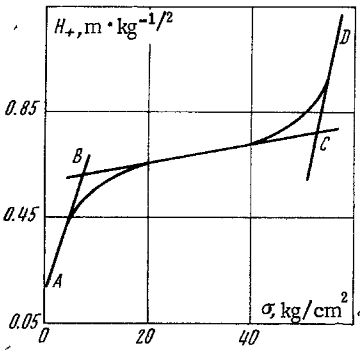

Fig. 3

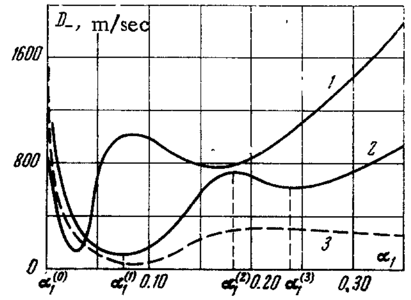

Fig. 4

For a specific soil type the latter criterion depends mainly on the degree of impregnation or free porosity of the soil.

The variation of the propagation speed of a moderate-intensity blast wave front (D_-) is shown in Fig. 4 for various free porosities (α_1) in sandy loam (curve 3). Also shown for comparison are the analogous variations in pure loam (curve 1) and sand (curve 2) according to the data of [5, 8, 9]. In the interval from $\alpha_1^{(0)}$ to $\alpha_1^{(1)}$ the propagation speed of the front drops abruptly due to the emergence of the free porosity and the increased compressibility of the sandy loam. In the interval from $\alpha_1^{(1)}$ to $\alpha_1^{(2)}$ the compressibility of the sandy loam decreases due to the capillary reinforcement effect, and the propagation speed of the front increases accordingly.

The decrease of D_- after the sandy loam reaches a free porosity $\alpha_1 = \alpha_1^{(2)}$ is attributable to reduction of the moisture menisci and of the capillary tension forces. The behavior of D_- for a free porosity $\alpha_1 > \alpha_1^{(3)}$ is determined by the development of rigid cementation bonds and lower compressibility of the sandy loam.

In heavy sandy loams the percentage content of finely disperse fractions increases, and the role of the capillary forces is diminished so the behavior of $D_- = D_-(\alpha_1)$ corresponds qualitatively to curve 1 in Fig. 4. In light sandy loams the cementation bonds for a free porosity $\alpha_1 > \alpha_1^{(3)}$ are poorly developed, and the propagation speed of the front is similar to the analogous dependence for sand (curve 2).

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