# PARAMETERS OF SHOCK WAVES CREATED BY EXPLODING HORIZONTAL CYLINDRICAL CHARGES IN A LOAM

A. A. Vovk, V. I. Kononenko,
I. A. Luchko, and V. A. Plaksii

The parameters of the shock waves created by exploding horizontal cylindrical charges in a loam have been experimentally investigated with allowance for the effect of the free surface. The effect of charge depth on the shock wave parameters is demonstrated.

The experimental data on the parameters of blast waves relate chiefly to the action of concentrated [1-7] or, in individual cases [7], vertical cylindrical charges exploded underground.

In our notation d is the particle diameter in mm, q is the particle content in percent, $\gamma_0$ is the soil density in g/cm$^3$, $\omega$ is the mass moisture content of the soil in percent, H is the depth of the charge in m, C is the weight of the charge per linear meter in kg, and R is the distance from the axis of the charge in m.

Below we present the results of an investigation of the parameters of cylindrical blast waves, with allowance for the effect of the free surface, in a loam of the following granulometric composition:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $d$, mm = | from | 1 | 0.5 | 0.25 | 0.05 | 0.01 | 0.005 |
| | to | 0.5 | 0.25 | 0.15 | 0.01 | 0.005 | < |
| $q$, % = | | 0.9 | 21.8 | 16.2 | 49.1 | 1.7 | 10.5 |

The variation of density and moisture content with depth is given below:

| | | | | | |
|---|---|---|---|---|---|
| $H$, m = | 0.10 | 0.20 | 0.40 | 1.00 | 1.30 |
| $\gamma_0$, g/cm$^3$ = | 1.94 | 1.95 | 1.96 | 2.07 | 2.12 |
| $\omega$, % = | 14,30 | 14.55 | 15.60 | 13.70 | 18.00 |

The following parameters were determined directly from the experiments: radial $\sigma_r$, tangential $\sigma_\alpha$, and axial $\sigma_z$ stresses, soil particle velocities v, maximum stress propagation velocities $D_m$.

The sensors for measuring the stresses and soil particle velocities were installed at the same depth as the charge at different points along a line perpendicular to the charge axis and dividing the length of the charge into two halves. They were lowered into boreholes 130 mm in diameter and suitably oriented relative to the charge, after which the boreholes were filled with the previously removed soil, which was tamped in layers to restore the natural density.

The stresses $\sigma_r$, $\sigma_\alpha$, $\sigma_z$ were measured as functions of time by means of high-frequency strain gauges, whose signals were amplified and recorded by an N-700 loop oscillograph. The velocity sensor was a metal case containing a solenoid, within which a permanent metal magnet moved freely. A more detailed description of these sensors is given in [4].

Applying to the experimental values of the blast-wave parameters the compatibility conditions at the shock front (on the distance interval investigated the blast wave is assumed to be a shock wave), we determine the volume deformation of the soil as a function of distance and the volume compression diagram. Knowing the volume strain and the volume compression diagram of the soil, we can determine the

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compaction zone and the dynamic load necessary to achieve the corresponding compaction. Experiments were conducted at the following values of C and H:

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| $C$, kg/m= | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 |
| $H$, m = | 0.56 | 0.35 | 0.85 | 0.21 | 0.70 | 0.70 | 0.50 | 1.00 | 1.20 | 0.30 |

where C is the weight of explosive per linear meter in kg and H is the depth of the charge in m.

A certain scatter of the experimental data obtained from similar experiments is unavoidable. The spread is chiefly associated with installation of the sensors. The results were correlated by the method of least squares.

The investigation revealed a power-law dependence of the stresses, soil particle velocities, and maximum stress velocities on the relative distance:

$$y = kR^{0\mu}, \quad y = \sigma_r, \sigma_\alpha, \sigma_z, v, \quad R^0 = RC^{-1/2} \tag{1}$$

Here, R is the distance from the charge axis in m. Values of the parameters k and $\mu$ are presented in the table.

| | $k_1$ | $-\mu_1$ | $k_2$ | $-\mu_2$ | $k_3$ | $-\mu_3$ | $k_4$ | $-\mu_4$ |
|---|---|---|---|---|---|---|---|---|
| $(\sigma_r)$ | 10.74 | 2.68 | 19.53 | 3.36 | 14.05 | 3.00 | 23.09 | 3.17 |
| $(\sigma_\alpha)$ | 3.44 | 2.58 | 6.89 | 3.00 | 6.69 | 2.66 | 7.03 | 2.24 |
| $(\sigma_z)$ | 6.37 | 2.58 | 11.00 | 3.09 | 10.74 | 2.68 | 16.18 | 2.84 |
| $(v)$ | 2.71 | 1.02 | — | — | 2.91 | 1.23 | 5.43 | 1.40 |
| $(H_i^\circ)$ | 0.21 | | 0.35 | | 0.70 | | 0.84 | |

The values of the parameters in the first row relate to $\sigma_r$, those in the second to $\sigma_\alpha$, those in the third to $\sigma_z$, and those in the fourth to v, while the fifth row gives values of the relative charge depth $H^\circ = HC^{-1/2}$ corresponding to pairs of values of k and $\mu$.

In Figs. 1, 2, 3, and 4 the radial (curves 1), axial (curves 2), and tangential (curves 3) stresses in kg/cm² are given as functions of the relative distance at a constant relative charge depth.

For $\sigma_r$, $\sigma_\alpha$, $\sigma_z$ the qualitative dependence on R° and H° is the same; therefore we need consider only the analysis of the radial stresses. It is clear from the curves that the radial stresses decrease sharply at values $R^\circ \leq 1.47$ m/kg$^{1/2}$, which indicates considerable losses of blast-wave energy in this region, chiefly as a result of soil compaction but also as a result of plastic deformation and heating of the soil. In the region $R^\circ \geq 1.47$ the shock wave gradually degenerates into a compression wave and the latter into an elastic wave.

In Fig. 5 the radial stress has been plotted against the relative charge depth. Curves 1, 2, and 3 correspond to values of the relative distance 0.98, 1.47, 1.96 m/kg$^{1/2}$.

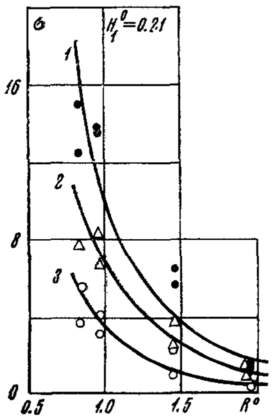

Fig. 1

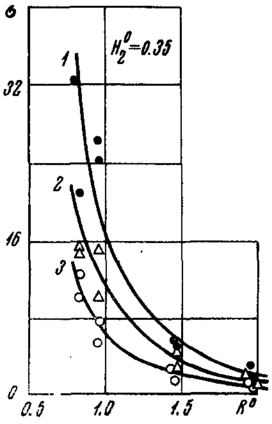

Fig. 2

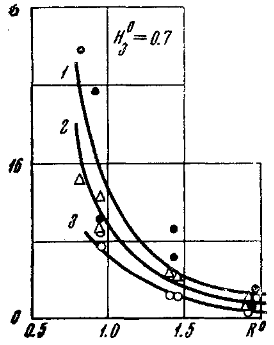

Fig. 3

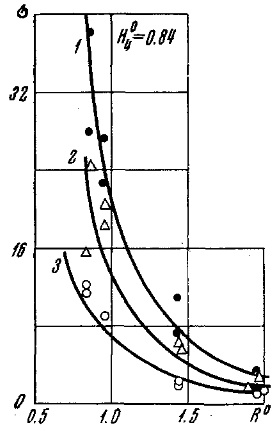

Fig. 4

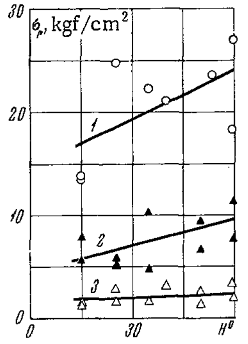

Fig. 5

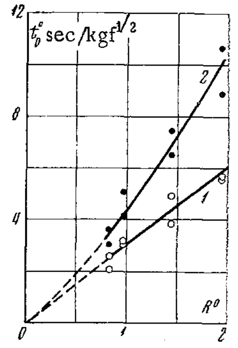

Fig. 6

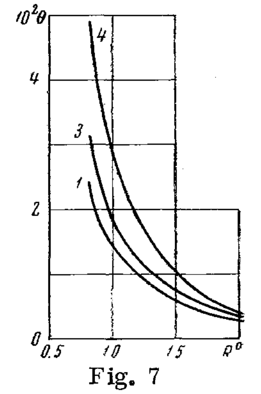

Fig. 7

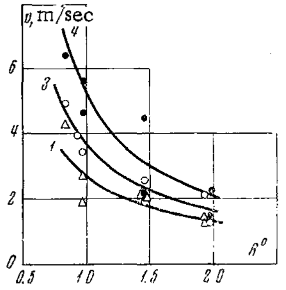

Fig. 8

Analytically these curves can be approximated by the following expressions:

$$\sigma_r = 0.276H^\circ + 9.08 \quad \text{at} \quad R_1{}^\circ = 0.98 \tag{2}$$

$$\sigma_r = 0.084H^\circ + 4.58 \quad \text{at} \quad R_2{}^\circ = 1.47 \tag{3}$$

$$\sigma_r = 0.020H^\circ + 1.42 \quad \text{at} \quad R_3{}^\circ = 1.96 \tag{4}$$

Here, $H^\circ = H/r_3$, $r_3 = 0.014C^{1/2}$, $r_3$ is the charge radius.

As may be seen from the graphs, at all the relative distances investigated there is a tendency for the stresses to increase with increase in charge depth. This indicates that we investigated only that range of depths $H^\circ < H^\circ_*$ at which the explosion characteristics were not those of a retained underground explosion. The inclination of the straight lines to the H°-axis is the greater, the smaller the distance R°. The chief influence on this aspect of the dependence of the stresses on H° and R° is exerted by the distribution of explosion energy in the directions of the free surface and the interior of the soil mass. This effect is especially important for points closer to the charge; in the region R° > 1.96 an elastic wave, whose energy forms a constant part of the explosion energy, is propagated, and therefore in this region the effect of the charge depth on the blast-wave parameters can be neglected.

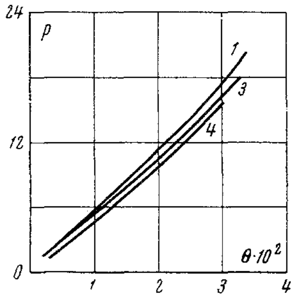

Fig. 9

In Fig. 6 the time $t_0$ of propagation of the onset of the disturbances (curve 1) and the time $t_m$ of propagation of the maximum stresses (curve 2) are shown as functions of the relative distance.

The corresponding equations of the curves have the form:

$$t_0^\circ = 10^3 t_0 / C^{1/2} = 3.06\,(R^\circ - 0.014),\quad t_m^\circ = 10^3 t_m / C^{1/2} = 4.54\,(R^\circ - 0.014)^{1.19} \tag{5}$$

where $t_0$ and $t_m$ are in msec.

Differentiating Eq. (5) with respect to t, we determine the propagation velocities of the disturbances and the maximum stresses, respectively,

$$D_0 = 326.80\ \text{m/sec}\quad D_m = 185.20\,(R^\circ - 0.014)^{-0.19} \tag{6}$$

From the compatibility condition at the shock front [2], using Eq. (6) for $D_m$ and the necessary coefficients for $\sigma_r$ from the table, we determine the volume strain at the shock front:

$$\theta = 1.65\cdot 10^{-2}\,\frac{(R^\circ - 0.014)^{0.38}}{R^{\circ 2.68}}\quad \text{at}\quad H_1^\circ = 0.21\ \text{m/kg}^{1/2} \tag{7}$$

$$\theta = 0.77\cdot 10^{-1}\,\frac{(R^\circ - 0.014)^{0.38}}{R^{\circ 3.00}}\quad \text{at}\quad H_3^\circ = 0.70\ \text{m/kg}^{1/2} \tag{8}$$

$$\theta = 3.10\cdot 10^{-2}\,\frac{(R^\circ - 0.014)^{0.38}}{R^{\circ 3.17}}\quad \text{at}\quad H_4^\circ = 0.84\ \text{m/kg}^{1/2} \tag{9}$$

The graphs corresponding to Eq. (7), (8), and (9) have been plotted in Fig. 7. As may be seen from a comparison of the curves, as the charge depth increases, so does the volume strain.

The graphs in Fig. 8 represent the soil particle velocity at the blast-wave front as a function of relative distance. The variation of the particle velocity as a function of charge depth is qualitatively the same as for the volume strain. This relationship indicates that on the range of relative charge depths and distances investigated the continuity equation

$$\theta = v / D_m \tag{10}$$

is satisfied.

The volume compression diagrams are presented in Fig. 9. The corresponding analytic expressions have the following form:

$$p = 833.70\theta^{1.09}\quad \text{at}\quad H_1^\circ = 0.21$$
$$p = 568.90\,\theta^{1.01}\quad \text{at}\quad H_3^\circ = 0.70$$
$$p = 587.10\,\theta^{1.04}\quad \text{at}\quad H_4^\circ = 0.84$$

Our analysis of the experimental data reveals that the conditions of generalized geometric similarity are satisfied for the blast-wave parameters. The laws obtained for the variation of volume strain with distance will serve as starting data for calculating the compaction zone in solving various engineering problems.

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