SPHERICAL BLAST WAVES IN SOILS INFERRED FROM STRESS AND STRAIN MEASUREMENTS

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We experimentally investigated spherical blast waves in soils of all basic types [1-4]. The stress components and the particle velocity were determined. For small stresses the strains were also measured [5]. We present below results of the experiments involving simultaneous measurements of the principal components of the stress and strain, which makes it possible to study the process of development of the soil strains in time at different distances from the point of explosion and also to obtain the $\sigma(\varepsilon)$ diagrams thus realized. It is shown that the maximum strains occur during the decrease of the stress; the residual strains may exceed values corresponding to the stress maximum; the compression and discharge diagrams $\sigma(\varepsilon)$ depend on the strain rate. The results indicate that both plastic and viscous properties of the soil exert significant influence on the propagation characteristics of blast

1. The Procedure of the Experimental Investigations. The experiments were conducted under field conditions in filled sandy soil of average coarseness with the skeleton density $\gamma = 1.42\text{-}1.48 \cdot 10^3$ kg/m^3 and moisture content W = 4-8% packed in a pit 1.8 m long, 1.5 m wide, and 1.8 m deep. The pits were dug in compacted loam. A spherical Trotyl charge of 0.2 kg mass was placed at a depth of 1 m and at a distance of 0.5 m from the nearest wall. The pit was cleared of the soil before each experiment and filled again in order to create identical soil conditions.

The normal (σ_r) and tangential (σ_α) components of the stress during the passage of the blast wave were measured by high-frequency tensometric sensors; the readings of the sensors were amplified and recorded on loop oscillographs.

The strains were recorded by sensors based on the time recording of the mutual displacement of two light plates located in the soil at a distance of 5 cm from each other. One of the plates was connected to a piston that moved within a cylinder connected to the other plate. The diameter of the cylinder is approximately eight times smaller than the diameter of the plates. The resistance of the cylinder to displacement is negligibly small compared to the resistance of the soil between the plates to compression. The mutual displacement of the plates was measured by wire tensoresistors, and their readings were recorded on a loop oscillograph.

The strain sensors are bidirectional, i.e., they can record both approaching and receding motion of the plates from each other. They were mounted in the soil parallel and perpendicular to the direction of propagation of the blast wave; this made it possible to measure the normal (ε_r) and tangential (ε_α) components of the strain. Along with the sensor plates a set of similar plates was placed in the soil for a control of their readings; these plates were not interconnected (free). They recorded residual displacements (determined during digging). In all cases the final displacements of the sensor plates and free plates were found to be equal, which confirms that the effect of interconnecting the plates (piston, cylinder) on the magnitude of the displacements is negligible.

The stress and strain sensors were placed at the same depth as the explosive charge at distances of 0.45, 0.6, and 0.75 m from it. Two sensors of each type were placed at each distance for recording σ_r, σ_α, ε_r, and ε_α. Furthermore, the stress sensors were arranged with a separation of 0.3 m. All the sensors were placed between the charge and the pit wall farthest from the charge. Another layer of soil of 0.2 m thickness was placed above the surface of the filled pit in order to ensure complete camouflet during the explosion.

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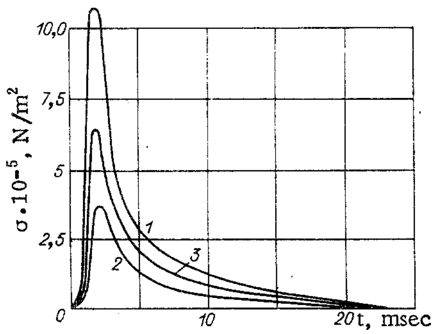

Fig. 1

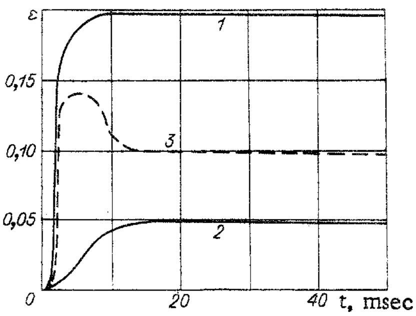

Fig. 2

2. Results of the Experiments and Discussion. The dependences of the stress and strain components on time obtained in one and the same experiment are shown in Figs. 1 and 2 for a distance of R = 0.45 m from the explosion point (reduced to a single scale of the oscillogram's copy). Curves 1-3 in Fig. 1 show the values of σ_r, σ_α, and the mean normal stress $\sigma = (\sigma_r + 2\sigma_\alpha)/3$; curves 1-3 in Fig. 2 show ε_r, ε_α, and the volume strain $\varepsilon = \varepsilon_r + 2\varepsilon_\alpha$, respectively. The signs of ε_r and ε_α are different, since a compression of the soil occurs along the radial direction and expansion along the direction perpendicular to it. Figure 1 shows that a precursor travels in advance; the magnitude of the jump at the precursor front is almost zero. The increase of the stress to the maximum value occurs after 1.5 to 2.0 msec, and the decay to zero occurs after 25-30 msec. The values of $\dot{\sigma}_r$ and $\dot{\sigma}_\alpha$ change with time on the segment on which the stress is increasing. At first they increase and attain their maximum values; then they decrease reaching negative values. The coefficient of lateral pressure $k_\tau = \sigma_\alpha/\sigma_r$ remains practically constant during the growth and decay of the stress, $k_\tau = 0.3$-0.4.

The strains increase more slowly than the stress. The maximum values of ε_r and ε_α occur at t = 8.5 msec and t = 15 msec, respectively, i.e., at significantly different instants of time. After attaining the maxima, ε_r and ε_α experience insignificant decrease. The volume strain has a maximum at t = 5 msec, after which it decreases approximately to 0.66 of the maximum value by t = 15 msec. At t = 2 msec, when the stress is maximum, the magnitude of the volume strain is about one third of its maximum value.

The time dependences of the stresses and strains at a distance R = 0.6 m from the point of explosion are shown in Figs. 3 and 4. Curves 1-3 give σ_r, σ_α, σ (Fig. 3) and ε_r, ε_α, ε (Fig. 4). The graphs of the strains are constructed from two experiments; therefore, the experimental points are shown. The general behavior of the graphs is the same as in Figs. 1 and 2. However, the stresses and strains increase more slowly. The stress maximum occurs at t = 4 msec; the maxima of ε_r, ε_α, and ε occur at t = 10, 25, and 7 msec, respectively. The volume strain decreases to approximately 0.05 of the maximum value by t = 25 msec. The coefficient of lateral pressure $k_\tau = 0.3$-0.4.

The graphs of the strain rate $\dot{\varepsilon}(t)$ are shown in Fig. 5. Curves 1 and 2 pertain to distances R = 0.45 and 0.6 m, respectively. The quantity $\dot{\varepsilon}(t)$ changes sign. In absolute magnitude the positive values are significantly larger than the negative values. However, the period of occurrence of negative values is larger.

The dependence of the maximum values of stresses σ_r on the distance can be approximately written in the form

$$\sigma_r = k\left(\sqrt[3]{Q}/R\right)^{\mu},$$

where Q is the mass of the explosive charge (kg), and R is the distance (m). Here $k = 4.5 \cdot 10^5$; $\mu = 3.3$. Similar values of the maximum stress were obtained earlier [4] in sandy soils of loose structure with $\gamma = (1.45$-$1.55) \cdot 10^3$ kg/m³ and W = 5-7%; in this case the constants in the above equations were $k = 6 \cdot 10^5$; $\mu = 3.2$.

It is difficult to determine the velocity of propagation of the wave front (start of the stress increase) from the oscillograms, since the magnitude of the stress jump at the front is almost equal to zero. The propagation velocity D of the value of the stress equal to 0.05 of the maximum to the investigated distances is about 100 m/sec. The propagation velocity of the stress maximum D_{max} varies from 80 to 55 m/sec. Similar values of the velocities — D = 110 m/sec and D_{max} = 60 m/sec [4] — were obtained earlier for sandy soils with $\gamma = (1.45$-$1.55) \cdot 10^3$ kg/m³ and W = 5-7%.

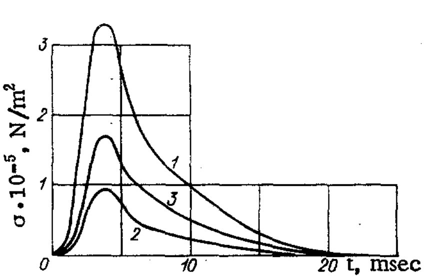

Fig. 3

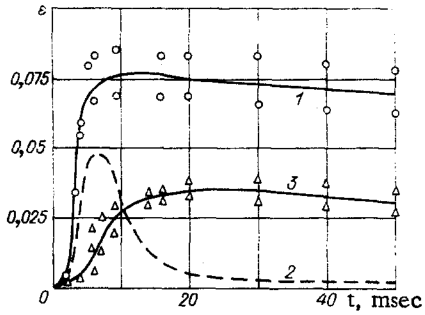

Fig. 4

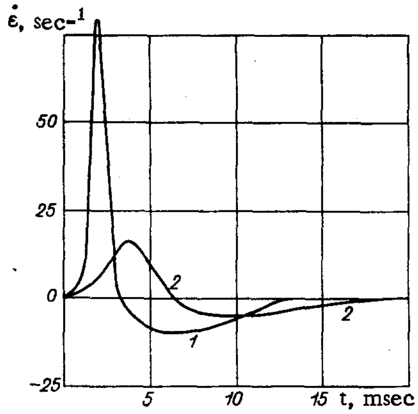

Fig. 5

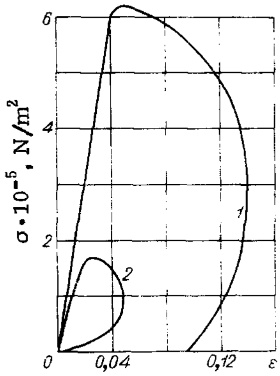

Fig. 6

The residual displacement of the soil, determined from the displacement of the free plates (during digging), at distances R from 0.25 to 0.75 m varied from 0.05 to 0.005 m. The deviations of the displacements of the individual plates from the mean values were up to 30%.

The tangential strain ε_α is related to the soil displacement S through the formula $\varepsilon_\alpha = S/R$. Differentiating with respect to time (R is the Lagrangian coordinate), we obtain the time dependence of the velocity of the particles:

$$u(t) = \dot{\varepsilon}_\alpha(t)R.$$

The mean velocity of the particles at R = 0.45 and 0.6 from the point of explosion, computed in accordance with the experimental values of $\dot{\varepsilon}_\alpha$ for time intervals Δt = 2 msec using the above equation, are given in Table 1.

The maximum values of the particle velocity occur during the period of decrease of the stress almost simultaneously with the maximum of the volume strain.

The dependence of the mean normal stress on the volume strain $\sigma(\varepsilon)$ corresponding to the values of $\sigma(t)$ and $\varepsilon(t)$ in Figs. 1-4 is shown in Fig. 6. Curves 1 and 2 pertain to distances R = 0.45 and 0.6 m. Different values of the strain rate correspond to the diagrams for different ε. In both cases the maximum strains exceed the values corresponding to the maximum stress. The residual strain at R = 0.45 m is 1.5 times larger than that attained at the stress maximum; at R = 0.6 m it is only 0.1 times as large.

The constant lateral pressure coefficient k_T obtained in the experiments corresponds to the Mises–Shleikher–Botkin plasticity condition; the application of this condition to soils was proposed in [6]. Actually, according to this condition the intensity of the tangential stresses, determined by the second invariant of the stress deviator I_2, is a function of σ:

$$I_2 = [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]/6 = \psi(\sigma).$$

In the case of spherical symmetry we thus get

$$(\sigma_r - \sigma_\alpha)^2/3 = \psi(\sigma),\ \sigma_r - \sigma_\alpha = F(\sigma) = [3\psi(\sigma)]^{1/2};$$

TABLE 1

t, msec	1	3	5	7	9	11	13	15	17	19
u(0.45), m/sec	0,8	1,8	3,2	2,5	1,8	1,0	0,5	0,1	—	—
u(0.6), m/sec	0,5	1,2	1,9	2,3	1,8	1,2	0,7	0,4	0,2	0,1

on the other hand, considering that $\sigma_\alpha = k_\tau\sigma_r$, we get

$$\sigma_r + 2\sigma_\alpha = \sigma_r(1 + 2k_\tau) = -3\sigma,\ \sigma_r - \sigma_\alpha = \sigma_r(1 - k_\tau),$$

$$F(\sigma) = -3(1 - k_\tau)\sigma/(1 + 2k_\tau).$$

The Mises–Shleikher condition is satisfied and the plasticity function is determined by the last equation.

The results obtained in these experiments show that the process of strain of the soil starts with its compacting at relatively small displacements. The maximum compacting occurs (at the investigated distances from the point of explosion) for displacement approximately equal to one third of the maximum value. A further increase of the displacement is accompanied by a decompacting of the soil and a decrease of its volume strain. At close distances from the point of explosion the decompacting is smaller than the preceding compacting and residual volume strains remain in the soil. At larger distances the compacting and decompacting become equal and residual volume strains do not occur.

The change of the particle velocity and volume strain with time lags the stress change. Their maxima occur during the period of stress decrease. The duration of the growth to the maximum for the stress, particle velocity, and volume strain increases with the distance from the point of explosion, i.e., a smearing of the wave occurs. The graphs of the volume compression and discharge $\sigma(\varepsilon)$ depend on the strain rate. They are different at different distances during increase as well as decrease of the stress.

These results confirm the view that the propagation characteristics of blast waves are determined by the plastic and viscous properties and this fact must be taken into consideration in refining soil models.

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