EXPERIMENTAL INVESTIGATIONS OF THE COMPRESSIBILITY OF ARGILLACEOUS SOILS SUBJECTED TO UNDERGROUND EXPLOSIONS

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Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, Vol. 9, No. 2, pp. 149–151, 1968

ABSTRACT: The results of experimental investigations of the compressibility of argillaceous soils (loess loams, loams, and clays) subjected to underground explosions are discussed. The data concerning the deformation at the shock-wave front, and their comparison with data concerning residual deformations indicate that the viscoplastic soil properties strongly influence the soil compressibility for short-term loads originating from underground explosions. The conclusions which were previously drawn in [1] are qualitatively and quantitatively confirmed.

1. Method and Conditions of the Experiments. The deformations at the shock-wave front propagating in the undisturbed ground during an underground explosion and, after the explosion, the residual deformations, were measured at various distances from the center of the explosion. In these experiments, the charges varied from 0.2 to 200 kg. Both the stress field and the particle velocities, as well as changes of these quantities in space and time were measured in the experiments. The principal radial stress σ_r and the principal tangential stress σ_α were measured with high-frequency membrane strain gauges with diameter D = 60 mm, height h = 20–30 mm, and membrane thickness δ = 2–7 mm. The signals of the strain gauges were amplified in a UTS-12 amplifier and recorded with N-102 and N-105 loop oscillographs. The radial velocities v of the particles were measured with sensors consisting of a solenoid which was housed in a Dural body and which carried a freely movable cylindrical permanent magnet inside the solenoid. N-102 and N-105 oscillographs were used to record the signals of these sensors. The sensors were placed in boreholes with diameters d = 150–200 mm at the dimensionless distances R_0 = 12, 15, 20, 30, and 40 from the explosion center. The notation is interpreted as follows: $R_0 = r/r_0$, with r denoting the distance from the explosion center in m, $r_0 = 0.054 \cdot C^{1/3}$ is the radius of the charge in m, and C denotes the weight of the charge in kg.

After the sensors had been appropriately arranged relative to the direction of wave propagation, the explosions were set off and the boreholes collapsed. The residual densities were measured by taking samples after the explosion at various distances from the explosion center; a standard method and a Litvinov field laboratory were employed.

The following data refers to the granulometric composition of the soil. The first line refers to heavy loess loams [1] with a volume weight of the matrix material γ = 1.35–1.47 g/cm^3 and a moisture content w = 12–14% by weight; the second line refers to loam with γ = 1.60–1.65 g/cm^3 and w = 10–15%; the third line refers to compact clay with γ = 1.70–1.75 g/cm^3 and w = 20–23%.

	0.5—0.25	0.25—0.1	0.1—0.05	0.05—0.001	0.001—0.005	0.005—0.001	less than 0.001
(1)	0.20	6.70		45.50	13.45	34.15	
(2)	26.70	36.46		26.60	1.27	8.97	
(3)	0.39	0.45	1.99	49.37	18.70	17.10	12.0

2. Results of the Investigations. The studies of the explosion-wave parameters revealed that in both loams and clays (as well as in the sandy loess soils of [2–4]), shock waves characterized by sharp, jump-like stress increases at the wave front occur at short distances from the explosion center. At increasing distances from the explosion center, the shock waves transform into continuous waves characterized by a smooth stress increase in the wave to a maximum value. The experimental data were used to verify the relations

$$\sigma_{r*}(R_0) = \rho_0 \cdot v_*(R_0) \cdot D_*(R_0), \quad \rho_0 = \frac{\gamma(1 + 0.01\,w)}{g} \qquad (2.1)$$

at the shock-wave front, where ρ_0 denotes the initial density and $D_*(R_0)$ denotes the propagation velocity of the shock-wave front. Below we list the corresponding average values $\sigma_{r*}(R_0)$ which were obtained from independent measurements ($\sigma_{r*}(R_0) \equiv \sigma_1$) or which were calculated with Eq. (2.1) from the particle velocities and the wave-front proppagation velocities ($\sigma_{r*}(R_0) = \sigma_2$) for the soils described above in lines (1), (2), and (3).

(1)	$R_0 = 10$	12	15	20	25	30
	$\sigma_1 = 30.7$	19.5	9.8	3.8	1.8	1.0
	$\sigma_2 = 37.0$	19.8	10.6	4.8	2.8	1.7
	$\Delta = +20.5$	+1.5	+8.2	+26.2	+55.5	+70.0

(2)	$R_0 = 15$	20	25	30		40
	$\sigma_1 = 22.0$	9.8	5.3	3.0		1.1
	$\sigma_2 = 27.1$	12.8	7.5	4.0		1.6
	$\Delta = +23.2$	+30.6	+41.5	+33.3		+45.5

(3)	$R_0 = 15$	20	25	30	40
	$\sigma_1 = 236$	92.2	45.0	27.2	6.9
	$\sigma_2 = 192$	58.2	25.9	12.6	4.8
	$\Delta = -18.6$	—37.0	—42.3	—53.5	—30.5

Here,

$$\Delta = \frac{\sigma_2 - \sigma_1}{\sigma_1}\ \%.$$

It follows from this data that Eq. (2.1) is quite well satisfied in our argillaceous soils at $R_0 \leq 15$–20, which corresponds to stresses σ_{r*} of 15–20 kg/cm^2 in loams, and 60–90 kg/cm^2 in clays. Similar stress figures, for which shock waves occur in loams, were stated in [5].

The shock waves permit one to determine the deformation at the wave front with the equation

$$\varepsilon_*(R_0) = \frac{\sigma_{r*}(R_0)}{\rho_0\, D_*^2(R_0)}. \qquad (2.2)$$

The quantities $\sigma_{r*}(R_0)$ and $D_*(R_0)$ in Eq. (2.2) are determined for argillaceous soils (as previously, for the sandy soils of [2, 3]) by the following empirical formulas

$$\sigma_{r*}(R_0) = K R_0^{-\mu_1} \frac{\text{kg}}{\text{cm}^2}\ 15 \leqslant R_0 \leqslant 40,$$

$$D_*(R_0) = \frac{54}{\mu_2 K_2 R_0^{\mu_2 - 1}} \frac{\text{m}}{\text{sec}}\ 7 < R_0 \leqslant 20. \qquad (2.3)$$

The coefficients are,

for loam:

$$K_1 = 42.6 \cdot 10^3, \quad \mu_1 = 2.81,$$

$$K_2 = 8.13 \cdot 10^{-3}, \quad \mu_2 = 2.12,$$

and for clay:

$$K_1 = 28.0 \cdot 10^5, \ \mu_1 = 3.45, \ K_2 = 0.58 \cdot 10^{-3}, \quad \mu_2 = 2.45.$$

The corresponding values for loess loam were stated in [4].

Figures 1 and 2 (curves 3) display the $\varepsilon_*(R_0)$ values constructed with Eqs. (2.2) and (2.3) for loess loam (Fig. 1) and for clay (Fig. 2). For the purpose of comparison, Figs. 1 and 2 include the residual deformaations $\varepsilon_0(R)$ which were experimentally determined at various distances from the explosion center. Points 1 and 2 of Figs. 1 and 2 correspond to the charges C = 1.6 and 0.26 kg, respectively.

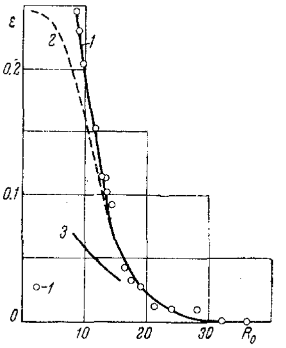

Fig. 1

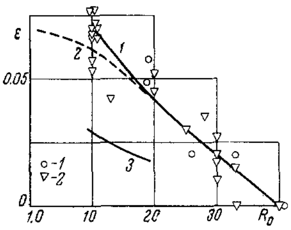

Fig. 2

The results were used to plot curve 1 which indicates the residual deformations $\varepsilon_0(R)$ as functions of the distance from the explosion center. We have $R = r/r_0$, where r denotes the distance from the center of the charge after the explosion (Euler coordinate). In order to compare $\varepsilon_0(R)$ with the deformations $\varepsilon_0(R_0)$ at the shock-wave front, we must plot the relationship $\varepsilon_0(R)$ in Lagrangian coordinates. By using the mass-conservation law, we obtain

$$R_0^3 = 1 + 3\int_{R_1}^{R} \frac{\eta^2 d\eta}{1 - \varepsilon_0(\eta)}, \quad R_1 = \frac{r_1}{r_0}, \qquad (2.4)$$

where r_1 denotes the radius of the cavity resulting from the explosion.

Curves 2 of Figs. 1 and 2 were constructed with Eq. (2.4) and correspond to the residual deformations $\varepsilon_0(R_0)$ in Lagrangian coordinates. A comparison of curves 2 and 3 of Figs. 1 and 2 with the corresponding values for loams [2] reveals that the residual deformations $\varepsilon_0(R_0)$ were much greater at R = 10–15 in loess soil than the deformations $\varepsilon_*(R_0)$ at the shock-wave front; in clay, the residual deformations were twice as great as the deformations at the shock-wave front, and, in loam, 1.3 times as great. This difference decreases with increasing distance R_0 and also with decreasing stress.

In the case of loess loam (Fig. 1), for which statistical test data are available [1], the residual deformations after the explosion did not exceed the deformations corresponding to a static load of magnitude equal to the maximum stress at the shock-wave front.

The results cannot be explained with the elastic-plastic model of [6]. They prove that the explosion-induced ground deformations continue to increase when the stress-removal condition $\partial\sigma/\partial t < 0$ is satisfied. The results confirm the previous conclusion [1] that time-dependent phenomena, particularly the deformation rate, strongly affect the volume compressibility of argillaceous soils subjected to short loads.

The author wishes to express his gratitude to Grigoryan for useful advice and to Mel'nikov for his participation in the experiments.

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17 April 1967 Moscow