DETERMINATION OF THE DYNAMIC COMPRESSIBILITY OF SOIL BASED ON THE PARAMETERS OF PLANE DETONATION WAVES

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A determination of the dynamic compressibility of soils based on the experimental values of the parameters of plane, cylindrical, and spherical detonation waves was carried out mainly for stresses not exceeding 80-100, and in specific cases, 250 kg/cm^2 [1-4]. Results are given below of an experimental investigation of plane waves for stresses of up to 1000 kg/cm^2. Based on this data we construct a stress–strain relation, corresponding to shock compression at the wave front. We determine the soil compaction. It is shown that the strain continues to grow behind the wave front. The remanent strains are greater than those that appear at the front. This gives evidence for the significant effect of viscous and plastic properties of the soil on the wave process.

1. Experimental Methods. The experiments were conducted in sandy soil of average coarseness packed into a foundation pit excavated in dense loam. The foundation pit was 1.1 m deep and 1 m long and wide. The gauges for measuring the stress were placed at a depth of from 5 to 70 cm from the top of the filled foundation pit. The sand was tamped in layers. Before each experiment the foundation pit was emptied and then refilled. Three gauges were placed at each depth: at the center and at distances of 25 and 45 cm from the center. In a row with the gauges there were placed aluminum plates 4 cm in diameter and 0.05 cm thick. We measured their residual displacement, assuming it to be equal to the displacement of the soil.

The stress was recorded with high-frequency strain gauges. The signals from the gauges after amplification were recorded on N-105 loop oscillographs. The diaphragms of the gauges were turned upwards.

Waves were produced by exploding over the foundation pit a plane charge of explosives of area 1×1 m^2. The explosion was triggered at the center. For a detonation velocity ~ 7000 m/sec the transit time of the wave up to the edge of the charge was ~ 0.07 msec. We used charges of thickness $\delta = 0.31$ and 0.19 cm, which corresponds to density C = 5 and 3 kg/m^2. Charges with $\delta = 0.31$ cm were placed directly on the surface of the foundation pit and in the air at heights 10 and 20 cm; charges with $\delta = 0.19$ cm were placed on the surface, and charges were also placed on the surface along with sprinkling of a layer of soil of thickness 40 cm and of length and width 1.8 m. The soil over the charge was not tamped.

The characteristics of the sandy soil were as follows: skeleton density $\gamma_0 = 1.62$-1.70 g/cm^3, moisture content w = 4-8%, density $\rho_0 = 1 + w = 1.76$ g/cm^3, which corresponds to the following content of components: gaseous $\alpha_1 = 0.28$, liquid $\alpha_2 = 0.1$, and solid $\alpha_3 = 0.62$. The loam in which the foundation pit is dug has characteristics $\gamma_0 = 1.76$-1.80 g/cm^3, and w = 8-15%. Experiments with sprinkling were carried out in the rainy season with $\gamma_0 = 1.62$-1.70 g/cm^3, w = 10-17%, and $\rho_0 = 1.85$ g/cm^2, which corresponds to $\alpha_1 = 0.17$, $\alpha_2 = 0.21$, and $\alpha_3 = 0.62$.

2. Experimental Results. After the explosion we observed an almost uniform residual displacement of the soil surface for all charges. The displacement at the edges was less than at the center by only 5-10%. The walls of the foundation pit collapsed at a depth of 2-3 cm.

The values of the mean residual displacements (in centimeters) of the surface of the foundation pit and the aluminum plates placed at different depths under the center of the foundation pit are presented in Table 1.

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TABLE 1

Conditions of the explosion	Thickness of charge, cm	Initial depth, cm							
		0	10	20	30	40	50	60	70
On the surface	0.31	6.4	4.9	3.8	3.0	2.4	1.8	—	—
	0.19	4.2	2.9	2.2	1.8	1.5	1.3	—	—
On the surface with sprinkling	0.19	13.0	11.2	9.5	8.0	6.7	5.7	4.7	3.9
At height 10 cm	0.31	5.3	4.2	3.3	2.5	2.1	1.6	—	—
At height 20 cm	0.31	4.1	3.3	2.7	2.9	1.8	1.5	—	—

TABLE 2

Conditions of the explosion	Thickness of charge, cm	Initial depth of the middle of the layer, cm						
		5	15	25	35	45	55	65
On the surface	0.31	1.95	1.87	1.81	1.73	1.73	—	—
	0.19	1.91	1.79	1.73	1.71	1.70	—	—
On the surface with sprinkling	0.19	2.03	2.00	1.95	1.91	1.85	1.85	1.81
At height 10 cm	0.31	1.87	1.84	1.81	1.74	1.72	—	—
At height 20 cm	0.31	1.78	1.74	1.72	1.70	1.69	—	—

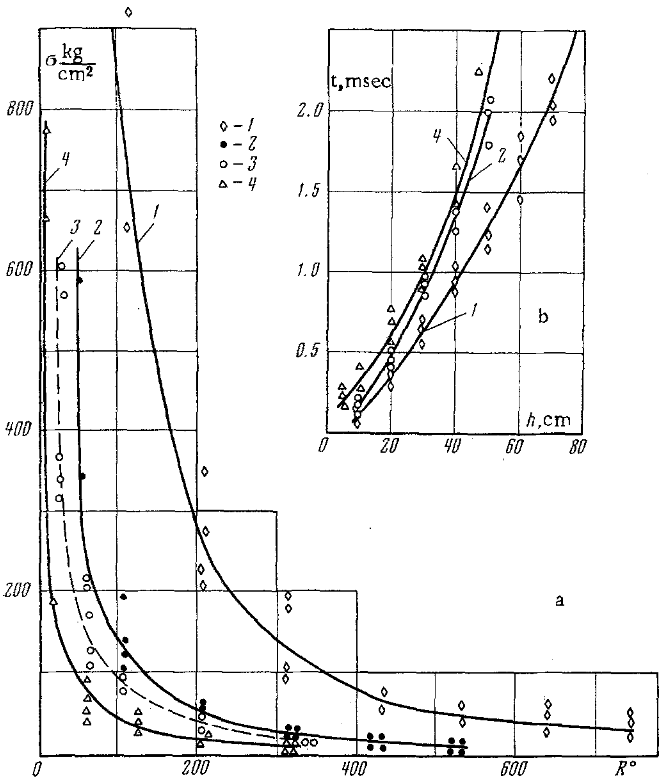

Fig. 1

At the edge of the foundation pit the displacements of the plates are 10-15% less than at the center; at a distance of 25 cm from the center and at the center, the displacements are practically the same.

Table 1 shows that when there is sprinkling the displacement increases by a factor of 3.5-4. The displacement decreases with increasing distance of the charge from the surface.

The residual displacements of the gauges proved to be 5-8% less than that of the plates, although the unit mass of the gauges is two orders greater. Thus, the residual displacements of the gauges are practically the same as for the surrounding soil.

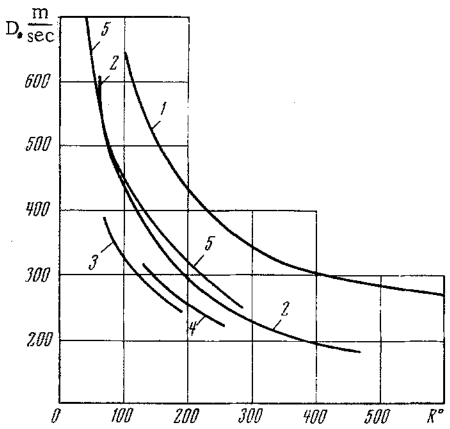

Fig. 2

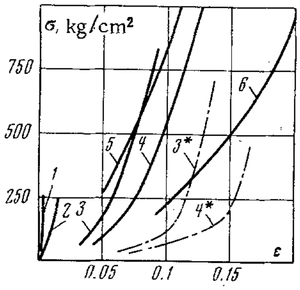

Fig. 3

We denote by γ the mean value of the density of the skeleton of the soil after an explosion in layers of thickness 10 cm, and we denote by y_1 and y_2 the values of the displacements of the upper and lower boundaries of the layer. We then have

$$\gamma = 10\gamma_0/[10 - (y_1 - y_2)].$$

Values of γ obtained from the data of Table 1 are given in Table 2.

The soil compaction depends considerably not only on the magnitude of the charge, but also on the conditions of the explosion. The amount of compaction is noticeably increased by sprinkling and decreased by the presence of an air layer. The soil was ejected to a height of 25-30 m. Thus we can assume that a further increase in the thickness of sprinkling leads to a certain additional increase in the soil density.

Over the entire investigated range of stresses, the waves in the soil are shock waves. The results of the measurements of the parameters of the waves are shown in Fig. 1a and b, and Fig. 2. In all cases curves 1 correspond to a charge with sprinkling for $\delta = 0.19$ cm; 2) corresponds to a surface without sprinkling, $\delta = 0.19$ cm; 3) in air at height 10 cm, $\delta = 0.31$ cm; 4) in air at height 20 cm, $\delta = 0.31$ cm; and 5) on a surface without sprinkling, $\delta = 0.31$. The dependence of the maximum stress at the front of a shock wave on the dimensionless distance $R^\circ = 2R/\delta$ is represented in Fig. 1a. The curve corresponding to a charge with $\delta = 0.31$ without sprinkling, practically coincides with the curve 2. The curves are constructed according to the readings of the gauges at the center of the foundation pit. At the edge the stress is 5-10% less than, and at a distance of 25 cm from the center it is the same as, at the center.

With sprinkling the stress increases by a factor of 5-6. An air layer 10 cm thick reduces the stress by a factor of 1.8-2.2, and a layer 20 cm thick reduces the stress by a factor of 3.5-3.8.

Figure 1b shows curves of the dependence of the path traversed by the shock wave on the time measured from the instant of detonation of the charge.

In Fig. 2 we plot the dependence of the velocity of wave front D on the dimensionless distance R°, constructed from the data of Fig. 1b, and also for other investigated cases. The curves refer to points at the center of the foundation pit. At the edges the values of the velocity are 10-15% less. A comparison of the curves in Fig. 2 shows that the presence of sprinkling leads to a considerable increase in the velocity of the wave front at all the distances investigated, curves 2 and 5 practically agree, and the air layer between the charge and the soil causes a decrease in the wave velocity in the soil. With increasing thickness of the layer the velocity decreases.

The obtained dependences $\sigma(R^\circ)$ and $D(R^\circ)$ allow us to construct experimental curves of the dynamic compressibility of the soil at the wave front $\sigma(\varepsilon)$, i.e., for $\dot{\varepsilon} \to \infty$. Using the relation at the front of the shock wave, we obtain the deformation of the soil, as a function of the stress and velocity of the front

$$\varepsilon = -\sigma/\rho_0 D^2.$$

The $\sigma(\varepsilon)$ curves, constructed in agreement with the last equation from the data of Fig. 1a and Fig. 2 are presented in Fig. 3. For a comparison we also give there curves of the dynamic compressibility of certain other soils. Curves 1 and 2, taken from [1], are constructed from the experimental values of the parameters of the shock waves in water-saturated sandy soils with $\alpha_1 = 0$, $\alpha_2 = 0.4$, $\alpha_3 = 0.6$ and $\alpha_1 = 0.01$, $\alpha_2 = 0.39$, $\alpha_3 = 0.6$. Curves 5 and 6 are obtained [5] for dynamic compression of a sample of a sandy soil, enclosed within a container with nondeforming walls. Curve 5 corresponds to soil with $\alpha_1 = 0.1$, $\alpha_2 = 0.32$, and $\alpha_3 = 0.58$, and curve 6 corresponds to soil with $\alpha_1 = 0.418$, $\alpha_2 = 0.02$, and $\alpha_3 = 0.58$. Curves 3 and 4 are constructed from experimental data (Tables 1 and 2); they refer, respectively, to soils with $\alpha_1 = 0.28$, $\alpha_2 = 0.01$, $\alpha_3 = 0.62$ and $\alpha_1 = 0.17$, $\alpha_2 = 0.21$, and $\alpha_3 = 0.62$.

The number of curves increases with decreasing moisture content, i.e., with increasing content of air in the soil. The specific weights of the skeleton for the soils to be compared differ imperceptibly.

Comparison of the curves in Fig. 3 shows that with increasing α_1, i.e., with decreasing moisture content, the curves first move away from the stress axis, and then, beginning approximately with $\alpha_1 = 0.17$, approach it, and for $\alpha_1 > 0.21$ again move away. A similar dependence was established earlier for stresses up to 30-40 kg/cm^2.

Curves 3* and 4* are determined from the data of Table 1. They correspond to residual deformations of the soil, the compressibility curves of which at the front of the shock wave are denoted 3 and 4.

From a comparison of the curves 3, 4 and 3*, 4* it follows that the residual deformations of the soil after the passage of the shock wave considerably increase the deformation obtained at the front. Earlier [6], a similar dependence was observed at smaller stresses. Thus, in the stress range up to 1000 kg/cm^2 after an uneven increase in deformations at the shock-wave front, during the period of decrease of stresses, there occurs a further increase in deformations. After a period of reduction of stresses and increase of deformations there evidently follows a period of simultaneous decrease in both these quantities. However the decrease in deformations is smaller prior to the increase.

The equation determining the compressibility of non-water-saturated soils for wave processes both for small and for large loads therefore represents a dependence not only between the stresses and the deformations, but also between their derivatives. Earlier a similar dependence was experimentally confirmed in the region of small stresses [1, 6-10]. From the general behavior of the curves in Fig. 3 it follows that a similar character of variation of deformation is also maintained for large stresses (several thousand atmospheres).

It is also shown that waves in the sandy soil being investigated packed in the foundation pit, excavated in denser loamy soil of unbroken structure, in the first approximation, are plane waves, if the charge overlaps the entire cross section of the foundation pit. The wave parameters at the center and at the edge of the foundation pit practically coincide. The effect of the walls of the foundation pit is similar to the effect of a smooth pipe – it results only in an insignificant decrease in the velocity of the front, the displacement of the particles, and the pressure at a distance of 4-5 cm from them. Earlier it was experimentally established [1] that if the area does not overlap the entire cross section of the foundation pit, then there will occur a noticeable distortion of the wave since the process is not one-dimensional, and at the charge boundaries, the values of the stress and velocity of the front decrease.

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