RESULTS OF EXPERIMENTAL INVESTIGATIONS OF THE MECHANICAL CHARACTERISTICS OF A SANDY SOIL UNDER STATIC LOADINGS

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The article gives the results of experimental investigations of the compressibility of a sandy soil of different moisture content under static loads with an intensity up to $\sigma_1 = 400$-600 kg/cm^2. The method is discussed and the construction of a pickup for the measurement of such stresses is described. It is shown that the trajectories of the loading with the monaxial compression of air-dry sand in the cases of loading and unloading do not coincide. For moist sandy soils it is shown that the condition of plasticity [1] is applicable right up to loads of $\sigma_1 = 400$-600 kg/cm^2 for both one-time and repeated loadings.

The experimental investigations were made in the Dynamic Testing Laboratory, Division of the Mechanics of Inelastic Media, Institute of Applied Mechanics, Academy of Sciences of the USSR, in a UDN-100 monaxial compression unit, being a further modernization of the UDN-150 unit described in [2]. In distinction from the UDN-150, the diameter of the sample in the UDN-100 unit is $D = 100$ mm, and the height $h_0 = 20$ mm. The new construction of the ring in which the sample is arranged, the piston transmitting the load to the sample, and the pickups for measurement of the components of the tensor of the stresses in the sample make it possible to broaden the range of the investigated stresses and deformations up to 10^3 kg/cm^2 and 0.5, respectively. A constructional scheme of the strain-gauge pickups of the rod-type for measurement of normal stresses with an intensity up to 10^3 kg/cm^2, developed for the UDN-100 unit, is shown in Fig. 1, where 1 is the housing of the pickup; 2 is the measuring element-rod; and 3, 4 are the working and compensating strain resistances. The measuring element is made of VT-12 titanium alloy with a yield point $[\sigma] = 165$ kg/mm^2, a modulus of elasticity $E = 2.4 \cdot 10^4$ kg/cm^2, and a limiting deformation $[\varepsilon] = 0.15$.

For the measurement of smaller principal stresses σ_2, pickups analogous in construction, mounted in a ring, were used. The contact surface of such a pickup had a curvature equal to the curvature of the internal surface of the ring.

The readings of the pickups were recorded through a UTS-VT-12/35 amplifier on an N-115 oscillograph. An evaluation was made of random errors connected with calibration of the pickups. The pickups were subjected to repeated loading up to 600 kg/cm^2 followed by unloading. The coefficient of variation with different degrees of loading ($\sigma_1 > 50$ kg/cm^2) did not exceed $k_V = 0.013$-0.017. The load on the samples was set up using a ZDM-30 testing machine. Large principal stresses $\sigma_1(t)$ were measured simultaneously by six pickups, $\sigma_2(t)$ by two pickups, and the displacements of the piston $u(t)$ by three pickups. The deformation of the sample was determined as $\varepsilon(t) = u(t)h_0$. The sample was loaded at a constant rate $\dot{\sigma}_1 = 0.32$ kg/(cm$^2 \cdot$ sec); the rate of deformation in the tests did not exceed $\dot{\varepsilon} = 1$-$2 \cdot 10^{-4}$ sec^{-1}. Provision was made for the threefold loading of exactly the same sample and for repeating an experiment five times under exactly the same conditions.

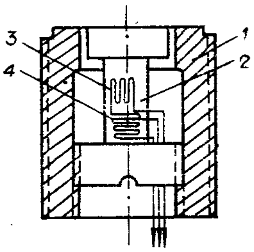

Fig. 1

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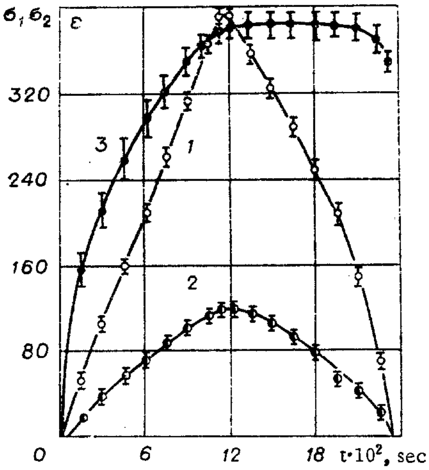

Fig. 2

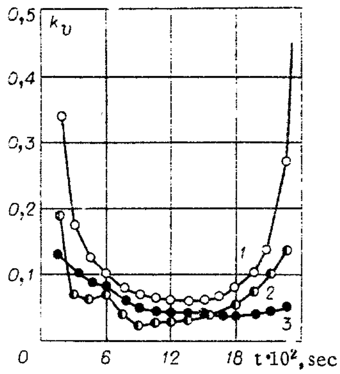

Fig. 3

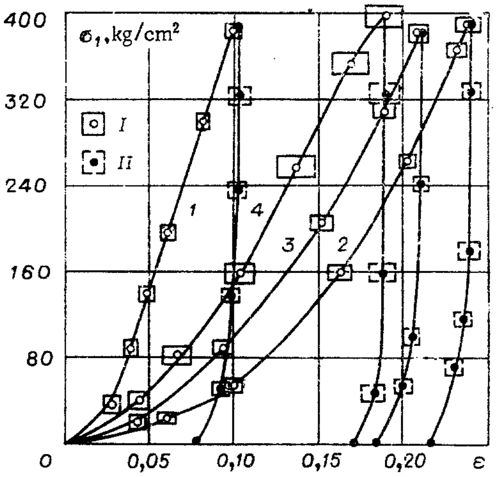

Fig. 4

Investigations were made of air-dry sand with a bulk weight $\gamma_0 = 1.54$ g/cm³ and a moisture content w = 0.003, as well as of wet sand with $\gamma_0 = 1.48$ g/cm³ and w = 0.05, 0.1, and 0.15. The results of the tests were analyzed statistically. The applicability of the hypothesis of a normal law of the distribution of the stresses and deformations for each moment of time t was verified using the Wilke criterion W [3].

Figure 2 gives the results of measurements of the stresses σ_1, σ_2, and the displacement ε, respectively, by curves 1-3 for a sample of sandy soil with $\gamma_0 = 1.48$ and w = 0.05, with corresponding confidence intervals, determined with a reliability $\beta = 0.9$. An analysis of the results of tests of samples of soil with w = 0.003, 0.05, 0.1, and 0.15 shows that the law of distribution for the stresses and the deformations for a fixed moment of time t can be taken as normal.

An idea of the accuracy of the measurements is presented in Fig. 3, which gives coefficients of variance k_V corresponding to $\sigma_1(t)$, $\sigma_2(t)$, and ε (t) (Fig. 2, curves 1-3). It follows from these data that, for the main part of the process, with the exception of small (in comparison with their maximal values) values of the stresses and deformations, the coefficients of variation do not exceed 0.05-0.10. For the series of tests, the relative confidence interval for the mathematical expectations of the stresses and deformations lies within the limits of 5-6%.

We note that, with dynamic tests of the same samples of soil in a UDN-100 unit at a rate of loading of $\dot{\sigma}_1 = 0.32 \cdot 10^4$ kg/(cm² · sec), the variation coefficients, corresponding to the value of $\sigma_1(t)$, did not exceed 0.10-0.12 [4]. A comparison of these data with data on the exactness of measurements of stresses in a sample of soil using pickups whose sensing element is a thin plate (for static and dynamic tests) [4] shows that, with large stresses, pickups of the rod type allow for a considerable increase in the range and accuracy of measurements of stresses.

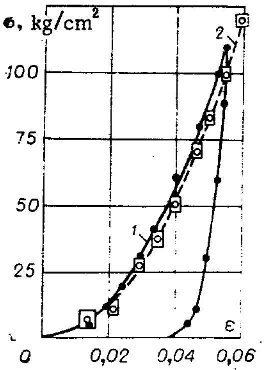

Fig. 5

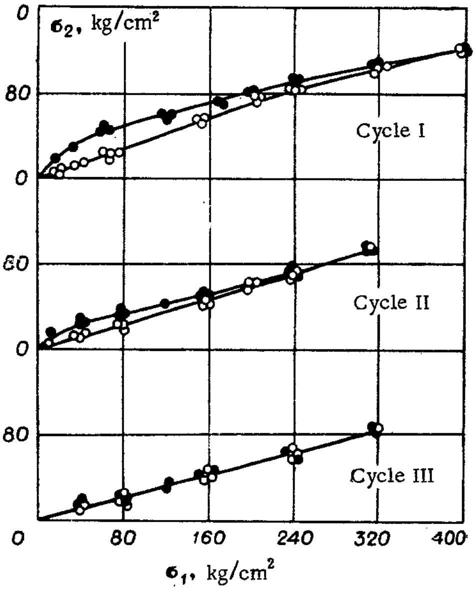

Fig. 6

TABLE 1

w	N	k	σ^*	Correlation coefficient		
				r	r_1	r_2
0,003	1	1,61	0,353	0,427	—0,397	0,841
	2	1,826	0,307	0,984	0,897	0,996
	3	1,855	0.301	0.974	0.841	0,994
0,05	1	1,767	0,319	0,987	0,952	0,994
	2	1,869	0,297	0,985	0,946	0,994
	3	1,907	0,289	0,988	0,956	0,995
0,1	1	1,851	0,302	0,870	0,816	0,992
	2	2,052	0,263	0,983	0,891	0,996
	3	2,02	0,268	0,923	0,858	0,981

Figure 4 gives the results of an investigation of the compressibility of a sandy soil with a different moisture content, obtained by elimination of the time t from the recordings of $\sigma_1(t)$ and $\varepsilon(t)$. Here curve 1 corresponds to an air-dry soil with $\gamma_0 = 1.54$ g/cm³ and $w = 0.003$; curves 2-4 correspond to a wet soil with $\gamma_0 = 1.48$ g/cm³ and $w = 0.05$, 0.1, and 0.15, respectively. The designation I corresponds to loading and II, to unloading, with corresponding confidence intervals for $\beta = 0.9$. From Fig. 4 it can be seen that, with an increase in the moisture content from $w = 0.05$ to 0.15, the deformations of the soil decrease. The change in the curvature of the curve $\sigma_1(\varepsilon)$ for a soil with $w = 0.15$ is due to the fact that, for $\sigma_1 \cong 250$-280 kg/cm², the moisture contained in the sample completely fills the pores of the soil and, with a further increase in the load, is displaced from the pores of the soil (the tests were made in accordance with an open scheme). The fact that the deformations of an air-dry soil were found to be less than the deformations of a wet soil is due, above all, to the smaller volumetric weight of the skeleton of the latter.

Repeated loadings of sandy soils with $\dot{\sigma}_1 = 3.2 \cdot 10^{-1}$ kg/(cm² · sec) and $\dot{\varepsilon} \cong 1 \cdot 10^{-4}$ sec⁻¹ showed that the branches of the diagram of $\sigma_1(\varepsilon)$ for unloading followed by loading do not coincide. With repeated loadings there is a certain increase in the deformations for exactly same loads. Thus, for soils with $\gamma_0 = 1.48$ g/cm³ and $w = 0.05$ with repeated loading with $\sigma_{1\max} = 400$ kg/cm², the maximal deformations rise in comparison with the first loading by 10%, and, with the third loading, by 14%; the residual deformations rise, respectively, by 12 and 15%.

It is of interest to make a comparison of the volumetric deformations of a sandy soil, obtained in the UDN-100 unit, with results obtained for the same soil in a volumetric-compression unit, where the soil is subjected to a uniform all-around pressure. The unit for such tests is described in [5]. The corresponding data for an air-dry soil are given in Fig. 5. Here, along the axis of abscissas, there is plotted the deformation ε, and along the axis of ordinates, the mean stress $\sigma = (1/3)(\sigma_1 + \sigma_2 + \sigma_3)$. Curve 1 was obtained in a volumetric-compression unit, $\sigma = \sigma_1 = \sigma_2 = \sigma_3$, curve 2 from the results of the test described above. It can be seen that, within the limits of the accuracy of the experiment, these curves coincide. Consequently, for an air-dry sandy soil with w = 0.003, the effect of shear, taking place in the UDN-100 unit, on the volumetric deformations with monaxial compression is insignificant.

Figure 6, in the plane of the principal stresses (σ_1, σ_2), shows the trajectories of the loading of an air-dry sandy soil with monaxial compression for three consecutive loading-unloading cycles. It can be seen that with the first two cycles, the trajectories of the loading and unloading of the sample do not coincide. The difference between these two branches of the loading trajectory is particularly considerable with small values of σ_1, and decreases from cycle to cycle. Thus, for the third cycle, within the limits of the accuracy of the experimental data, the branches of the trajectory coincide. For the second and third cycles, the loading branch of the trajectory of the loading is described quite well by a linear dependence. In the first cycle, a linear dependence between σ_1 and σ_2 is followed for $100\ \mathrm{kg/cm^2} \leq \sigma_1 \leq 400\ \mathrm{kg/cm^2}$. For $\sigma_1 < 100\ \mathrm{kg/cm^2}$, this dependence becomes nonlinear with unloading and differs considerably from the trajectory of the loading. Consequently, the frequently used postulation of the simple trajectories of the loading with the monaxial deformation of an air-dry soil, is not exact strictly speaking, and there is need for an all-around experimental verification.

For wet sandy soils with w = 0.05-0.15, the result was obtained that the branches of the trajectory corresponding to loading and unloading of the sample coincide practically everywhere, except for a small region of small values of σ_1, and the dependence between σ_1 and σ_2 in the region of plastic deformation has a linear character in the range $0 \leq \sigma_1 \leq 400\ \mathrm{kg/cm^2}$. The measurements of $\sigma_2(t)$ and $\sigma_1(t)$ thus make it possible to construct the functions of the plasticity for the sandy soils investigated. The condition for plasticity with analysis of the experimental results was taken in the form of the Mises–Schleicher condition [1]

$$\ddot{I}_2 = (1/6)F^2(\sigma).$$

The results of the investigations showed that, for $\sigma_1 > 25\ \mathrm{kg/cm^2}$, with an accuracy sufficient for practical applications, the loading and unloading correspond to exactly the same dependence $F(\sigma) = k\sigma + b$, where k and b are coefficients characterizing the internal friction and the adhesion. The corresponding values of the coefficients k, the coefficients of the lateral pressure $\xi = \sigma_2/\sigma_1$, as well as the coefficients of the correlation r and their confidence intervals r_1, r_2 for the linear regression F with respect to σ for three consecutive loadings of samples of soil of different moisture content are given in Table 1. With an exactness up to the random errors of the experiments, the values of the coefficient b are equal to zero.

From the data presented it can be seen that, with an increase in the moisture content from 0.003 to 0.1, the value of the coefficient k with the first loadings increases by 1.2 times. Repeated loadings also lead to a certain increase in the value of k from the first cycle to the second. However, these differences in the values of k for sandy soils with w = 0.05-0.1 are 9-10%, which lies practically within the limits of the accuracy. For a sand with w = 0.003, this change is somewhat greater, and amounts to 13%. The small values of the correlation coefficients for this sand confirm the earlier conclusions with respect to the difference in the loading and unloading trajectories in the plane (σ_1, σ_2). There were practically no differences in the values of k for the second and third loadings.

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